PHYSICS OF THE EARTH

A SERIES of related monographs prepared under the direction of various committees of the National Research Council.

The following were published as bulletins of the National Research Council and may be obtained from the Publication Office, National Research Council, Washington, D. C. Please send remittance with order.

No. 77. VOLCANOLOGY. 77 *pages*. Paper, $0.75; cloth, $1.

No. 78. THE FIGURE OF THE EARTH. 286 *pages*. Paper, $3; cloth, $3.50.

No. 79. METEOROLOGY. 289 *pages*. Paper, $3; cloth, $3.50.

No. 80. THE AGE OF THE EARTH. 487 *pages*. Paper, $4.50; cloth, $5.

No. 85. OCEANOGRAPHY. 581 *pages*. Paper, $4.50; cloth, $5.

No. 90. SEISMOLOGY. 223 *pages*. Paper, $2; cloth, $2.50.

The series is continued with the following two books published by the McGraw-Hill Book Company, Inc.

INTERNAL CONSTITUTION OF THE EARTH. 413 pages.

TERRESTRIAL MAGNETISM AND ELECTRICITY. 778 pages.

PHYSICS OF THE EARTH—VIII

Terrestrial Magnetism and Electricity

EDITED BY J. A. FLEMING
Director, Department of Terrestrial Magnetism, Carnegie Institution of Washington

Contributors

J. BARTELS
University of Berlin

L. V. BERKNER
Department of Terrestrial Magnetism

J. A. FLEMING
Department of Terrestrial Magnetism

O. H. GISH
Department of Terrestrial Magnetism

H. D. HARRADON
Department of Terrestrial Magnetism

C. A. HEILAND
Colorado School of Mines

E. O. HULBURT
Naval Research Laboratory

H. F. JOHNSTON
Department of Terrestrial Magnetism

H. E. McCOMB
U. S. Coast and Geodetic Survey

A. G. McNISH
Department of Terrestrial Magnetism

W. J. ROONEY
Department of Terrestrial Magnetism

B. F. J. SCHONLAND
Bernard Price Institute of Geophysics

O. W. TORRESON
Department of Terrestrial Magnetism

L. VEGARD
University of Oslo

FIRST EDITION

McGRAW-HILL BOOK COMPANY, INC.
NEW YORK AND LONDON
1939

Copyright, 1939, by the
McGraw-Hill Book Company, Inc.

PRINTED IN THE UNITED STATES OF AMERICA

*All rights reserved. This book, or
parts thereof, may not be reproduced
in any form without permission of
the publishers.*

THE MAPLE PRESS COMPANY, YORK, PA.

FOREWORD

It is generally agreed that more attention should be given to research in the middle ground between the sciences. Geophysics—the study by physical methods of the planet on which we live—is a conspicuous instance of such a middle-ground science, since it shades off imperceptibly in one direction or another into the fields of physics, astronomy, geology, to say nothing of biology, with which the subject of oceanography is closely connected. Some branches of geophysics, such as meteorology, terrestrial magnetism, geodesy, and oceanography have long had a more or less independent existence, but it has become increasingly clear that these subjects, and many others, are all parts of geophysics. For various reasons, among which may be mentioned the development of geophysical methods in prospecting for oil and minerals, there has lately been a considerable development of interest in geophysics, but this development has not been matched by the publication in English of systematic treatises on the subject. With these ideas in mind, Dr. J. S. Ames, during his term as Chairman of the Division of Physical Sciences of the National Research Council, was instrumental in organizing in 1926 a large committee to prepare a series of bulletins on The Physics of the Earth, the purpose being "to give to the reader, presumably a scientist but not a specialist in the subject, an idea of its present status together with a forward-looking summary of its outstanding problems."

In due course subcommittees were formed to prepare reports on the following subjects:

- The Figure of the Earth
  - Gravity, Deflection of the Vertical and Isostasy
  - Tides, Ocean, and Earth
  - Variation of Latitude
- Seismology
- Terrestrial Magnetism and Electricity
- The Age of the Earth
- Field Methods for Detecting Unhomogeneities in the Earth's Crust
- Internal Constitution of the Earth
- Meteorology
- Oceanography
- Volcanology

That this project, as ambitious as it is important, is now coming to fruition with the publication of these bulletins is due partly to the skill and farsightedness with which Dr. Ames selected the committee and assisted in outlining its program; partly to the care and interest with which Dr. Ames's successor, Professor Dayton C. Miller, directed the committee's activities during his term as Chairman of the Division; and particularly to the devotion with which the chairmen and members of the several subcommittees have carried out their respective assignments. The hearty thanks of the National Research Council and of the readers of these bulletins are due the several authors for their efforts.

The members of the Subsidiary Committee of the Division of Physical Sciences on Terrestrial Magnetism and Electricity, responsible for preparation of the present volume, are: John A. Fleming (Chairman), F. Leroy Foster, O. H. Gish, D. L. Hazard, C. A. Heiland, E. O. Hulburt, H. E. McComb, W. J. Peters, and W. F. G. Swann. As will be noted, the Subsidiary Committee has been fortunate in securing the services of J. Bartels, L. V. Berkner, H. D. Harradon, H. F. Johnston, A. G. McNish, W. J. Rooney, B. F. J. Schonland, O. W. Torreson, and L. Vegard as contributors in addition to its own members.

CONTENTS

Page
Foreword v

Preface xi

CHAPTER I

The Earth's Magnetism and Magnetic Surveys by J. A. Fleming 1

I. Introduction 1
II. Early history 1
III. Magnetic field of the Earth 3
IV. Time-changes of the magnetic field 5
V. Secular variation 7
VI. Magnetic surveys 13
VII. Movement of secular-variation foci—isoporic changes 24
VIII. Magnetic anomalies and geologic features 28
IX. Solar diurnal variation 33
X. Smaller periodic variations—lunar-day and annual 39
XI. Irregular variations and magnetic activity 42
XII. Solar activity and Earth's magnetic state 49
XIII. Conclusion 53

CHAPTER II

Magnetic Instruments by H. F. Johnston, J. A. Fleming, and H. E. McComb 59
I. Instrumental requirements 59
II. Early history 64
III. Types of instruments 66
IV. Practice at magnetic observatories 103

CHAPTER III

Magnetic Prospecting by C. A. Heiland 110
I. Introduction 110
II. Magnetic properties of rocks 113
III. Magnetic instruments 118
IV. Corrections in magnetic prospecting 131
V. Theory of interpretation 134
VI. Results of magnetic surveys 143

CHAPTER IV

Atmospheric Electricity by O. H. Gish 149
I. Historical introduction 149
II. General survey 155
III. Electrical conductivity of the atmosphere 164
IV. The electric field of the atmosphere 210
V. The electric current in the atmosphere 226

CHAPTER V

INSTRUMENTS USED IN OBSERVATIONS OF ATMOSPHERIC ELECTRICITY by O. W. Torreson . 231
I. Introduction 231
II. Potential-gradient apparatus 233
III. Conductivity-apparatus 241
IV. Ion-counters 252
V. Nuclei-counters 258
VI. Ionization-apparatus 262
VII. Space-charge apparatus 267
VIII. Air-earth current determinations 268
IX. Auxiliary apparatus 269

CHAPTER VI

EARTH-CURRENTS by W. J. Rooney 270
I. Introduction 270
II. Historical 270
III. Measurements 272
IV. Results of observations 289
V. Relation of earth-current and magnetic variations 302
VI. Present status of earth-current investigation 306

CHAPTER VII

ON CAUSES OF THE EARTH'S MAGNETISM AND ITS CHANGES by A. G. McNish 308
I. Introduction 308
II. Harmonic functions 309
III. The permanent magnetic field of the Earth 314
IV. Secular variation of the Earth's magnetic field 325
V. The solar and lunar diurnal variations of the Earth's magnetic field 334
VI. Induction of electric currents within the Earth 355
VII. Magnetic disturbances 359

CHAPTER VIII

SOME PROBLEMS OF TERRESTRIAL MAGNETISM AND ELECTRICITY by J. Bartels 385
I. Introduction 385
II. Relations to the ionosphere 386
III. Terrestrial-magnetic activity and the Sun 387
IV. General features of a magnetic field 399
V. Magnetic storms 401
VI. Solar diurnal variation, S, and lunar diurnal variation, L 409
VII. The permanent field and secular variation 421
VIII. Observations of magnetic fluctuations between 10,000 and one cycle per second . 429
IX. Earth-currents and air-earth currents 430

CHAPTER IX

RADIO EXPLORATION OF THE EARTH'S OUTER ATMOSPHERE by L. V. Berkner 434
I. Introduction 434
II. Historical background 439
III. The Breit-Tuve experiment 441
IV. Multifrequency method of determining ion-distribution 442
V. Double refraction in the ionosphere 446
VI. Automatic multifrequency methods and the records produced 448
VII. The general nature of the ionosphere 450
VIII. The E- and F_1-regions 454

PAGE
IX. The F_2-region 457
X. Radio fade-outs accompanying bright chromospheric eruptions 464
XI. Sporadic intense E-region ionization 469
XII. Ionospheric effects coinciding with magnetic storms 474
XIII. Scattered reflections 481
XIV. Reflections of short retardation 482
XV. Rôle of ionized regions in radio transmission 483

CHAPTER X

THE UPPER ATMOSPHERE by E. O. Hulburt 492
I. The meteorology of the upper atmosphere 492
II. The ionosphere 501
III. The theory of the ionosphere 514
IV. Skip-distances of radio waves 528
V. Electrodynamics of the upper atmosphere 531
VI. Solar diurnal variation of terrestrial magnetism 536
VII. Lunar variation of terrestrial magnetism 545
VIII. Magnetic storms and aurorae 547
IX. Zodiacal light and gegenschein 564
X. Atmospheric ozone 568

CHAPTER XI

THE AURORA POLARIS AND THE UPPER ATMOSPHERE by L. Vegard 573
I. Introduction 573
II. Space-time distribution of the aurorae and their solar and terrestrial relationships 574
III. Theory of the aurorae 588
IV. Electric rays, their properties, origin, and constitution in relation to the theory of aurorae and magnetic disturbances 601
V. The auroral spectrum and its interpretation 616
VI. Some remarkable variations of intensity within the auroral spectrum 633
VII. Auroral spectrum and the upper atmosphere 641

CHAPTER XII

THUNDER-CLOUDS, SHOWER-CLOUDS, AND THEIR ELECTRICAL EFFECTS by B. F. J. Schonland 657
I. Electric fields and field-changes at the Earth's surface 657
II. The charge on rain 661
III. The breakdown field in the presence of drops 661
IV. The charges developed and other electrical quantities involved in the thunder-cloud 661
V. The distribution of charge on the thunder-cloud 664
VI. The origin of the cloud-charges 666
VII. The mechanical power available for the generation of charge 670
VIII. Interchange of electricity between electrified clouds and the Earth 670
IX. Interaction of charged clouds with the ionosphere 671
X. Electromagnetic radiation-atmospherics 672
XI. Emission of electrified particles—effect on penetrating radiation 672
XII. Distribution and frequency of thunder-storms 674
XIII. Lightning 675

CHAPTER XIII

BIBLIOGRAPHICAL NOTES AND SELECTED REFERENCES by H. D. Harradon 679
I. Introduction 679
II. Classification of bibliography 680

PAGE
III. International bodies 681
IV. American Geophysical Union 684
V. Publications of observatories and institutions 684
VI. Scientific journals and memoirs 689
VII. Bibliographies and abstracts 692
  A. Terrestrial magnetism 693
  B. Terrestrial electricity 724
  C. Geophysical prospecting 747
  D. Ionosphere 749
  E. Cosmic radiation 758
  F. Radioactivity 763
  G. Ozone 764
  H. Miscellaneous 765

INDEX 779

PREFACE

The complex nature of the Earth's magnetic and electric fields has long puzzled and intrigued investigators. A cursory glance at the subjects of the chapters of this volume will indicate how far-reaching are the problems. Of the geophysical sciences, that dealing with the nature of the Earth's magnetism and electricity is outstanding in its relations to cosmical phenomena. Unlike some sciences, its lack of ready evidence to any of the human senses makes it a difficult subject to present in even a semi-popular treatment. The attempt has been made to inform the reader of what is known and the ways along which further research is and may be profitably directed. In common with the other volumes in the series "Physics of the Earth," the aim has been to provide, not a textbook, but a reference book which may stimulate and enlist the interest of a larger group of investigators in terrestrial magnetism and electricity.

The various authors have approached their subjects from many viewpoints. Naturally there will be some overlapping in the treatments and some differences of opinion. Repetition has been eliminated so far as has been possible without interfering with the continuity of thought. Many features in the rapid developments of theory and experiment in the field and in the laboratory of more recent years pave the way for different interpretations by investigators. It is increasingly apparent, however, that, although such differences of interpretation may seem great, they tend toward a harmonious integration in the solution of moot questions. The increasing importance of the application of experimental approach through research outside the Earth's surface is well evidenced by those chapters dealing with the upper atmosphere.

The chapter on bibliographical notes and selected references includes only the outstanding references in the very large literature of the subject scattered through many scientific reports and magazines in all parts of the world. The first part summarizes—a unique feature in a bibliography—the many sources of publication bearing on, and the many international, national, and private organizations interested in terrestrial magnetism and electricity. These notes and references form a most valuable research tool.

The Subsidiary Committee charged with the preparation of this volume has found the task difficult but lightened by unselfish aid from many sources. In particular, it is indebted to the Carnegie Institution of Washington, which has made freely available the vast store of research, illustration, record, and compilation of its Department of Terrestrial Magnetism during the 35 years of that department's activities.

Besides the contributors who have so generously given of their time in the preparation of the various chapters, the Committee is indebted to many other investigators and organizations for permission to make free use of their research and data. The members of the staff of the Division of Terrestrial Magnetism and Seismology of the United States Coast and Geodetic Survey must be mentioned; their splendid and long-continued work provides a constantly growing and rich mine of data and demonstrates how necessary is coordinated and planned operation in this field of Earth physics.

The Committee is also indebted to the Division of Physical Sciences for the opportunity to prepare this volume on terrestrial magnetism and electricity and for its patience during the long interval necessary for the assembling of the manuscripts.

For the excellence of the illustrative matter, the authors have to thank W. C. Hendrix for the preparation of the line drawings and maps, and P. G. Ledig and J. W. Green for the photographic work.

Should this volume encourage wider interest in research in geomagnetism and geoelectricity, the Subsidiary Committee and the authors will feel well repaid.

JOHN A. FLEMING.

WASHINGTON, D.C.,
July, 1939.

CHAPTER I

THE EARTH'S MAGNETISM AND MAGNETIC SURVEYS

J. A. Fleming

Department of Terrestrial Magnetism, Carnegie Institution of Washington

I. INTRODUCTION

There is about the Earth a magnetic field. Its cause and origin are veiled in mystery as in the case of that other great natural phenomenon, gravitation. Unlike the latter, one cannot immediately recognize the Earth's magnetism through any physical sense. An unexpected fall apprises one of the existence of gravitation but no bodily effect is noticed in the Earth's magnetic field, although it is real as that of gravity and is subject to relatively greater local anomalies than the gravimetric field.

The familiar compass-needle demonstrates that magnetic forces are present everywhere in the Earth. Ocular evidence of such force may also be obtained by its inductive magnetic action upon a material highly susceptible to such action, for example, an alloy with unusually great capacity for transient induced magnetization in weak magnetic fields such as that of our planet. Permalloy has been developed in recent years to supply the need of such a material to improve communication by cable. When a thin long rod of permalloy is directed toward the north magnetic pole of the Earth's field, the magnetization induced in the bar because of that field is quite sufficient to lift small pieces of permalloy. But as the rod is turned with its length at right-angles to the field and thus in the direction least favorable to induction, it loses the magnetism induced by the Earth and will no longer support such metal strips, which fall.

The picture of magnetic phenomena is incomplete if viewed only in a man-made laboratory, even though we can now produce there, within a space of a cubic inch, an artificial magnetic field which is about 100,000 times more intense than that of the Earth. Fortunately, Nature provides not only the Earth and its atmosphere as a great magnetic laboratory but also continuously performs experiments, utilizing as apparatus the Sun, the Moon, and radiations from space. It is, however, only within historic times that we have appreciated the opportunity of putting this great laboratory to human use.

II. EARLY HISTORY

The discovery of the lodestone—the ore magnetite—with its mystical power of attracting particles made of iron paved the way to the development of the magnetic compass, which has been in use by navigators since the eleventh century. Various traditions ascribe knowledge of this magnetic property of the lodestone—the "leading stone" of the Scandinavians, the "loving stone" of the French—to the Chinese as much as 2,600 years before the Christian era, and to the Japanese during the second half of the seventh century, but there is some question as to their authenticity (see Chapter II-I).

This property of the lodestone was early known in Greece. Advantage of it appears to have been taken in connection with certain mysteries, particularly those of the Phrygian miners who settled in Samothrace, where, as a proof of supernatural skill, the attractive phenomena of the lodestone were exhibited through the working of the so-called Samothracian rings. A more inquiring attitude, however, was taken by Thales of Miletus (640–546 B.C.) who, in ancient times, enjoyed the appellation of the Father of Philosophy and to whom is attributed, among other achievements, the first prediction of a solar eclipse. He is represented as pondering on a theory—not based on supernatural influences—to account for this attractive power of the lodestone and there is a statement by Aristotle to the effect that "Thales, too, as is related, seems to regard the soul as somehow producing motion for he said that the stone has a soul since it moves iron." The magnet, therefore, has a place at the very inception of philosophy. Although a number of references to the attractive property of the lodestone are to be found in ancient Greek literature, it is now generally believed that the Greeks had no knowledge of the polarity of the magnet or of its directive property in the Earth's field upon which the use of the compass depends.

In the attempt to solve the mystery of the lodestone it was discovered that, when it was mounted in a block of wood and floated in water, one direction would always be indicated, that is, magnetic north and south (see Chapter II-I). This was followed in about 1269 by the first European treatise on the magnet.

That property of the magnetic field of the Earth giving direction to the compass-needle was thus utilized some centuries before Columbus began his voyages to the Western Hemisphere. He, however, was apparently the first to determine that the compass did not point true north except in certain places. There is the story of the threatened mutiny on his first transatlantic voyage when the crew saw the compass pointed 10° west of true north instead of north as indicated by the pole-star, and how he shifted the compass-card on its needle during the following night, thus quieting the fears of his men and inducing them to continue. In doing this Columbus was taking chances, for laws had been framed against falsifying the compass. In one of these curious statutes, mariners were charged not to eat onions or garlic lest the odor "deprive the lodestone of its virtue by weakening it and prevent them from perceiving their correct course." The punishment for violations seems barbarous in the extreme, for the culprit "if his life were spared must be punished by having the hand which he most uses fastened by a dagger thrust through it to the mast, to be withdrawn only by tearing it free." Even today there are many who think of the compass-needle as showing direction "true to the pole of the heavens or the polar star."

Magnetic dip or inclination was unknown until 1576, when Robert Norman, a practical seaman and instrument-maker, published "A newe discovered secret and subtill propertie concernying the declinying of the Needle, touched therewith under the plaine of the Horizon." His discovery that the magnetic needle, when mounted on a horizontal axle so as to be free to move in the vertical plane, dipped below the horizon gave the first hint that the source of the magnetic field of the Earth might be within the globe and not in the stars as previously supposed.

It was not until 1600, however, that William Gilbert published his famous volume in which he pointed out that the Earth itself acts to a certain extent as though it were a great spherical magnet. Gilbert's conclusion thus preceded Newton's announcement of universal gravitation.

III. MAGNETIC FIELD OF THE EARTH

The magnetic field extends far out into space. Four thousand miles above us it is still one-eighth as great as at the surface. One may picture it as made of innumerable lines of magnetic force or action closely packed as schematically shown in Figure 1. These lines of force are parallel to the surface near the plane of the equator, but as they approach the magnetic poles they bend and converge.

Taken as a whole, the Earth is a feeble magnet. It is possible to magnetize our modern hard steel ten-thousand fold or more as much. Even so, since the globe is large, its total magnetism is equivalent in effect to 800 quintillion parallel one-pound magnets of our best magnet-steel, could they be placed at its center or, were they evenly distributed throughout the Earth's body, with one such magnet in about every two cubic yards.

However, the Earth is not uniformly magnetized and the principal magnetic poles are distant 1,200 miles or more from its geographic poles. The north magnetic pole, first visited over a century ago in June, 1831, by Ross and again in 1903, by Amundsen, is on Boothia Peninsula in northern Canada. The south magnetic pole, in South Victoria Land of the Antarctic Continent, has not yet been visited. Thus the magnetic poles are not diametrically opposite each other, the line joining them passing some 750 miles away from the center of the Earth.

The Earth's outer crust or shell is not homogeneous and therefore is not uniform in its magnetic behavior. Thus there are many regions of local magnetic disturbance, such as are caused by magnetic ore-deposits, some so great as to give rise to local poles and other irregularities in the general magnetic field.

The study of the character and behavior of this field therefore calls for observations not only on the surface of our globe but also in its interior and in its atmosphere. This applies particularly to the higher atmospheric limits and to the Earth's enveloping skin or crust, where we apparently must look for explanations of those constantly occurring regular and irregular variations with time of the magnetic field.

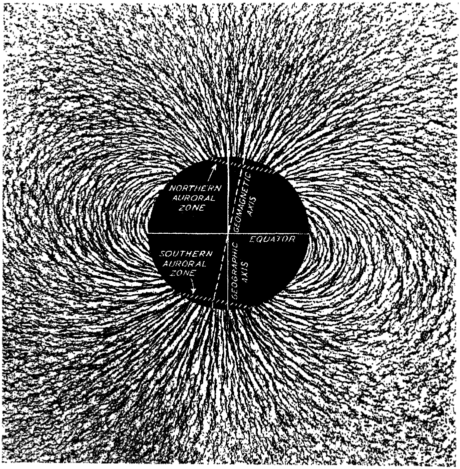


FIG. 1.—The magnetic field about the Earth.

Measurements to determine completely the Earth's magnetic field at any point must include observations which will define its direction in space and its magnitude. Thus we must determine the three magnetic elements. These are (see Chapter II, Fig. 1): (1) Magnetic declination, D—often incorrectly called "variation" by navigators—that is, the angle between the true astronomical north-south meridional plane and the vertical plane through the magnetic north-south direction as defined by the compass; (2) magnetic inclination or dip, I, the angle through which a magnet entirely free to move would dip below the horizon in the magnetic north-south meridional plane; and (3) the total magnetic force, F, acting in the magnetic meridional plane, or its horizontal component, H, or its vertical component, Z.

IV. TIME-CHANGES OF THE MAGNETIC FIELD

That the Earth's magnetic field is subject to progressive change or secular variation, that is, a slow age-long variation, was first noted by Gellibrand in 1634. In a book published in London (June 12, 1634) entitled "A Discourse mathematical on the Variation of the Magnetical Needle together with its admirable Diminution lately discovered" he announced for the first time that "variation is accompanied with a variation." Besides the secular variation, other more or less regular time-changes include daily variations, taking place chiefly during daylight and

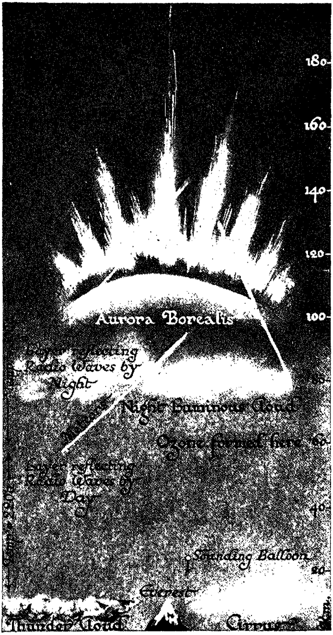


FIG. 2.—The heights of various phenomena in the atmosphere (*after Dobson*).

varying in magnitude and character with geographic position, with the seasons of the year, and with disturbances on the Sun. There are also short-period, long-period, and sudden-commencement disturbances, commonly designated magnetic storms, apparently accompanying solar disturbance and other cosmical phenomena.

Much of what is known concerning time-changes can best be visualized graphically. Many of the photographic records upon which conclusions are based are in effect motion pictures of the experiments constantly being performed by Nature in her great laboratory. It is therefore desirable to give first some explanation of one method in common use to represent any quantity which varies with the passage of time or with some other variable. Consider, for example, any period over which a certain quantity is observed. It may be for centuries, for years, for months, for days, for minutes, or for any other period represented by a straight reference-line as the one from T_o to T_n in Figure 3-*A*. That line may be divided into a number of equal parts each corresponding to the selected time-unit, for example, in hours, in which case T_o represents 0^h or midnight of the day and T_n the following midnight. Each hour is then represented at successive points $\frac{1}{24}$, $\frac{2}{24}$, $\frac{3}{24}$, . . . of the length, T_oT_n, measured from T_o. On the lines at right-angles to this line at any of

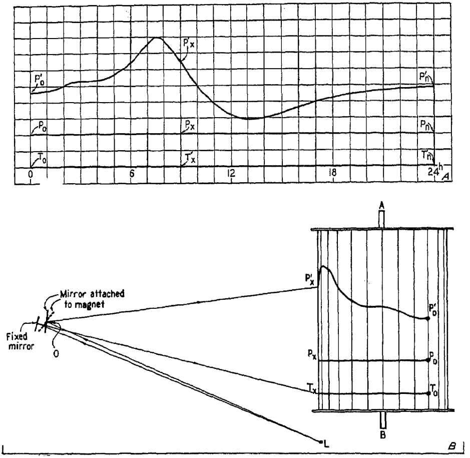


FIG. 3.—(*A*) Graph of data varying with time; (*B*) schematic diagram to show principle used to record magnetic variations.

these points then may be plotted to any arbitrarily chosen scale the difference between this reference-line and the observed value at any time, T_x. The phenomenon being one in which there is no change during the time represented, the graph representing it would be a straight line such as P_oP_n parallel to T_oT_n. For some phenomenon not constant during the time-interval being considered, the line joining values plotted to our arbitrary scale on perpendiculars at the successive unit-times to represent the changing values will form some regular or irregular curve such as $P'_oP'_xP'_n$.

In an instrument to record change in compass-direction, consider Figure 3-*B* as a horizontal projection of a mirror attached to a magnetic needle, the latter so suspended at a point above the paper as to be free to rotate about its vertical axis at *O*. Suppose a source of light at *L* providing a horizontal light-beam directed toward the mirror; when the compass-direction changes through a small angle, the mirror rotates with it from some position as that shown by the heavy dotted line, and the reflection of the light-beam changes from OP'_o to OP'_x. A second mirror, fixed in position, causes a steady reflection of the light-beam to give a reference-line corresponding to T_oT_n. Now if a sheet of photographic paper, suitably protected from all light except the reflected beam, be so mounted as to have uniform motion either in the vertical plane or on a cylinder rotating on an axle, *AB*, then as the compass-direction changes, the light-beam focused on the sensitive paper gives a photographic record as the paper shifts. Upon developing this sensitized sheet we have a complete record of the movement of the compass-needle during the period. It is comparatively easy to determine by experiment or measurement of distances the length of the perpendicular to the reference-line of such a record for a unit angular motion as, for example, a single minute of arc or any other unit of measure.

When such a method as outlined is translated into an actual instrument, as in Figure 4, the optical and photographic recording devices intrinsically constitute substitutes for very long magnets which would be difficult to support so that they might swing freely with changes in the Earth's field. The length of the magnet in such a variometer as shown by Figure 4 is less than an inch, but with the optical arrangement this may become theoretically infinitely long. Some actual photographic records of daily variations of the direction of the compass (magnetic declination) and of the forces acting in the vertical and horizontal planes are reproduced in Figure 5.

V. SECULAR VARIATION

The usefulness for navigation at sea of magnetic direction or declination as indicated by the compass has stimulated and maintained interest in determining its value since the time of Columbus. Before the invention of chronometers it was thought that geographic position might be derived from knowledge of changes from place to place in magnetic declination and inclination. This led to the first systematic oceanic survey by the astronomer Edmund Halley in the Atlantic Ocean, during 1698–1700, on the sailing vessel *Paramour Pink*. As one result of his voyages the first isomagnetic chart, reproduced* in Figure 6, was published. It

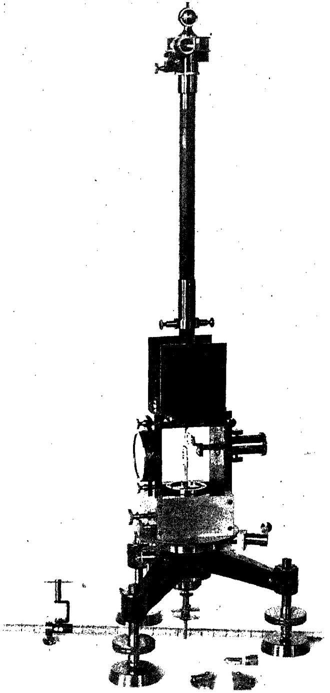


FIG. 4.—Variometer as used to record changes in compass-direction.

---

* Because of the difficulty in photographing the original and reduction in reproduction, the dedication, title, etc., are not quite legible and are quoted below:

(1) Dedication at right: "Majestati semper Augustae GULIELMI III D. G. Magnae

showed lines at all points on which the compass-direction differed from true north by the same angle, that is, lines of equal magnetic declination or isogonics. This chart and succeeding ones based on later data from time to time show the progressive changes in the position of these lines—changes known as secular variation. Figure 7, for declination, is based on the latest isomagnetic chart published by the United States Hydrographic Office and applies for the epoch 1930. Its contrast with Halley's

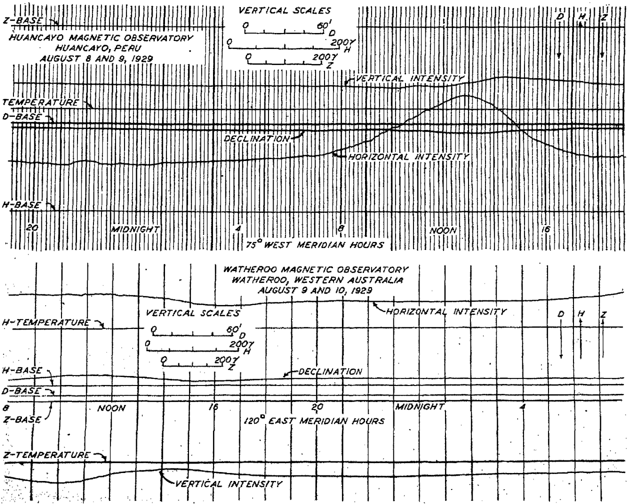


FIG. 5.—Magnetograms for typically quiet days.

Britanniae Fra. Hib. Regis Invictissimi Tabula haec Hydrographica Variationum Magneticarum Index Devotissime consecratur a subdito Humillimo Edm. Halley"

(2) Main title at center left: "A new and correct chart shewing the Variations of the Compass in the Western and Southern Oceans as observed in the year 1700 by his Ma^{ties} command by Edm. Halley"

(3) Explanation at top left: "The curve lines which are drawn over the Seas in this chart do shew at one view all the places where the Variation of the Compass is the same. The numbers to them shew how many degrees the needle declines either eastwards or westwards from the true north and the double line passing near Bermudas and the Cape de Verde Isles is that where the needle stands true without Variation"

(4) Note at bottom left: "The sea in these parts abounds with new forms of animals of a middle species between a bird and a fish having necks like swans and swimming with their whole bodies always under water only putting up their long necks for air"

chart strikingly indicates the great accumulation of observed values during the past three centuries. The corresponding chart to show lines of equal dipping of the magnetic needle, or magnetic inclination—isoclinic chart—is reproduced in Figure 8; note particularly the line of the magnetic equator so strikingly different from the geographic equator. The isodynamic chart of Figure 9 shows the lines of equal horizontal intensity and with the charts of Figures 7 and 8 defines the Earth's magnetic field at any point in the area covered.

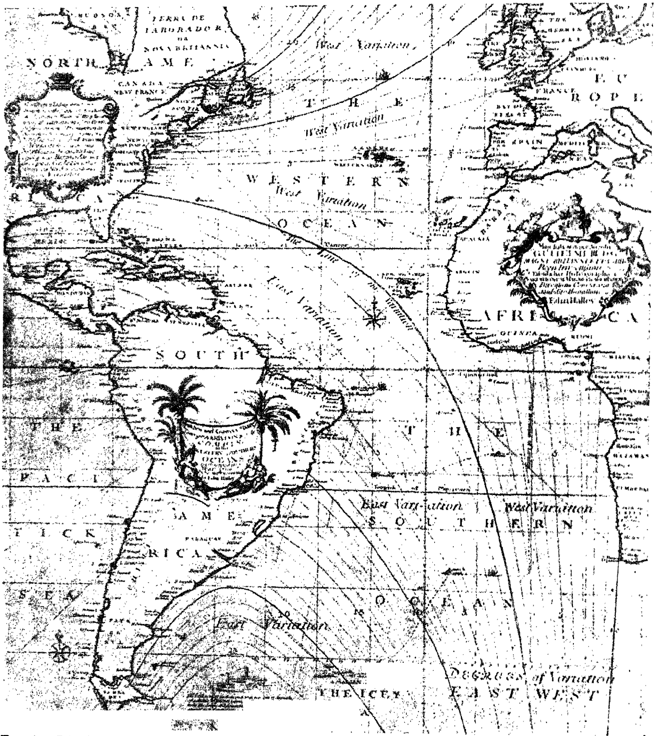


FIG. 6.—The first isomagnetic chart based on observed data showing lines of equal compass-direction or declination.

The secular changes in the compass-direction in earlier times are indicated by Figure 10, showing change with time in the position of the agonic lines and by Figure 11, along several different parallels of latitude for various epochs.

Another picture of secular variation utilizing observed compass-directions at London and at Boston is given by Figure 12 showing the observed true bearing of the compass in different years. The importance of these changes in any practical use of the magnetic compass or needle may be realized by considering the observed data at London. There the magnetic needle pointed 11° east of north in 1580, changed gradually until it pointed 24° west of north in 1818, and since then has shifted eastward and now points only about 11° west of north. These results might be taken to indicate a complete cycle of change of about 500 years, but centuries more of observations are needed to verify such an indication.

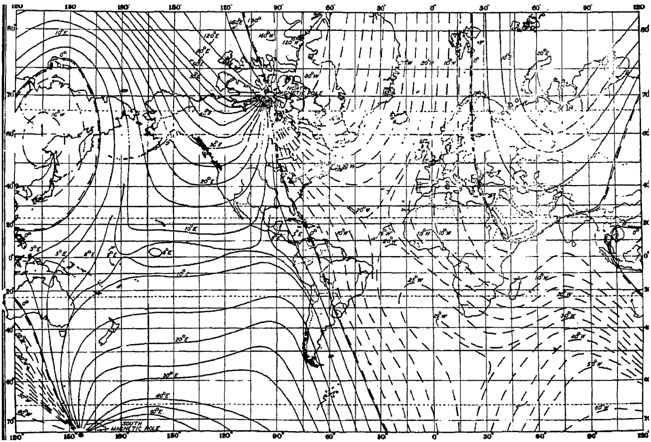


Fig. 7.—Isomagnetic chart, lines of equal declination or isogonics, epoch 1930 (*after United States Hydrographic Office*).

For the purpose of illustration, conceive a thin, giant compass-needle about two miles long supported at its center by a pivot on which it is free to rotate, its north-seeking end taking at all times the direction of the Earth's magnetic field. The north end of this giant needle would move a little less than 100 feet for a change of one degree in direction or about one and one-half feet for a change of one minute of arc. At London its end would have moved westward from 1580 to 1812 more than 3,200 feet and then about 1,300 feet eastward to 1938. In Washington the annual change at present is such that the end of such a giant needle would move because of it only about one-sixth of an inch per day toward the west, or a total of about five feet in the year. In the past 50 years this motion here would have totaled some 400 or 500 feet—a long city block—from the east.

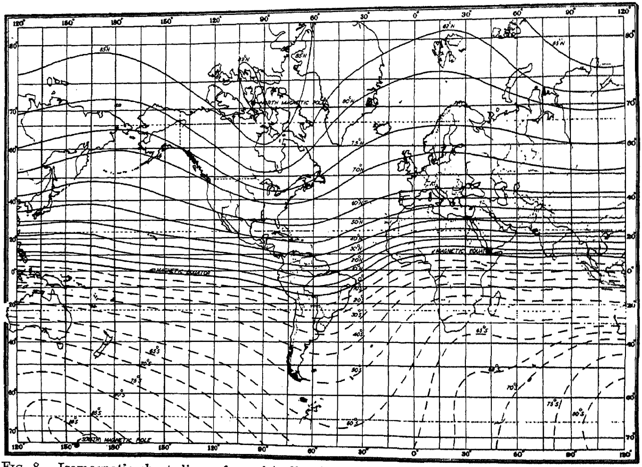


FIG. 8.—Isomagnetic chart, lines of equal inclination or isoclinics, epoch 1930 (*after United States Hydrographic Office*).

A more illuminating graphical method, developed in an early paper by Bauer to represent observed data, is illustrated in Figure 13. In this the magnetic needle is considered as being supported at its center so as to be free to turn in any direction in space. The changing position of a needle so mounted would show, by the motion of its end, secular variations in both the horizontal and vertical planes. At London such a needle would have described a conical surface in a clockwise direction. However, similar graphs for other stations in various parts of the world show different periods and amplitudes of this motion in space. Thus, note the secular changes at Potsdam, Germany, as in Figure 14. So we may not assume a cyclic secular-variation of common period applying to the whole Earth. We must, therefore, dismiss as insufficient the popular notion that changes in compass-direction arise wholly or mainly from a shift in the position of the magnetic axis or of the magnetic poles of the Earth.

VI. MAGNETIC SURVEYS

During the past quarter-century marked progress has been made in accumulating accurate and coordinated information which is beginning to shed light on the character of the changes in the magnetic elements, particularly in those regions controlled by the more advanced nations.

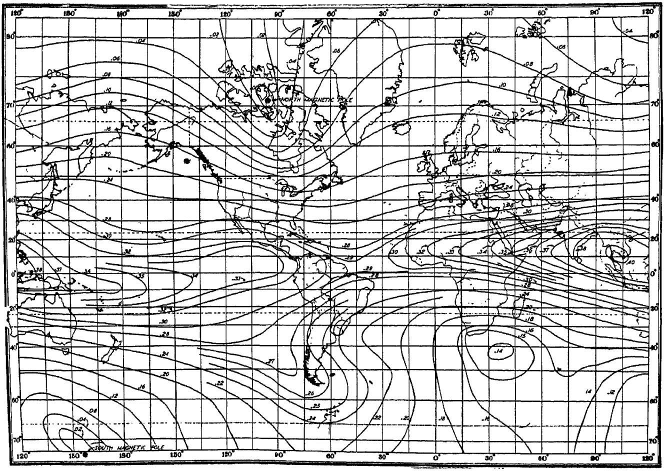


FIG. 9.—Isomagnetic chart, lines of equal horizontal intensity or isodynamics, epoch 1930 (*after United States Hydrographic Office*).

Any attempt, however, to arrive at a solution by examining what takes place within a limited area or during too short an interval of time is not only a hopelessly inadequate undertaking but is likely to lead to erroneous suppositions as regards long-period magnetic changes. It is but another instance of the danger of drawing conclusions from half-truths so aptly illustrated by the often-quoted dispute of the

> . . . six wise men of Industan to learning much inclined
> Who went to *see* the elephant though all of them were blind.

Like the subject of that classical investigation, this is also of mammoth proportions, and like those seekers for truth, investigators of magnetic changes have given clear and valuable reports of what has come within

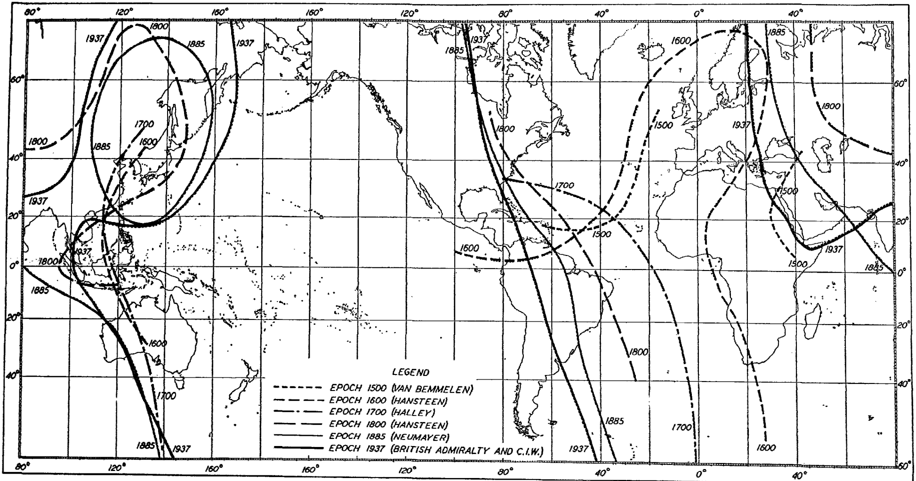


FIG. 10.—Progressive change (secular variation) of lines of zero magnetic declination (agonics) (the dots indicate the side of the agonic lines on which the declinations were easterly).

their observation, each of which is essential to the construction of the complete picture. But as vision improves with the gradual accumulation of details, the complex character of the subject begins to become apparent, and some real progress toward a reconciliation of the differences in first impressions may now be expected.

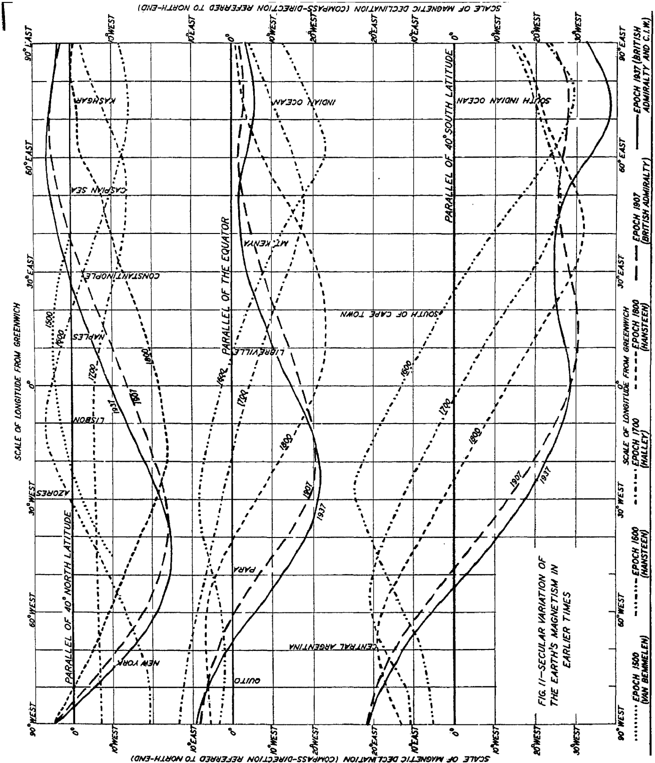


FIG. 11.—Secular variation of the Earth's magnetism in earlier times.

As stated, the scattered observations of declination run back over 300 years in a few limited localities. The collection of observations of inclination, owing of course to its smaller practical utility as well as to the greater difficulty attending its measurement, is much less abundant. It is now some 100 years since Gauss first described a method of obtaining

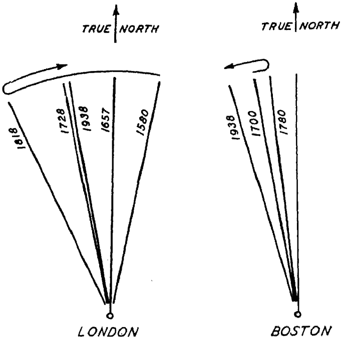


FIG. 12.—Secular variation of compass-direction.

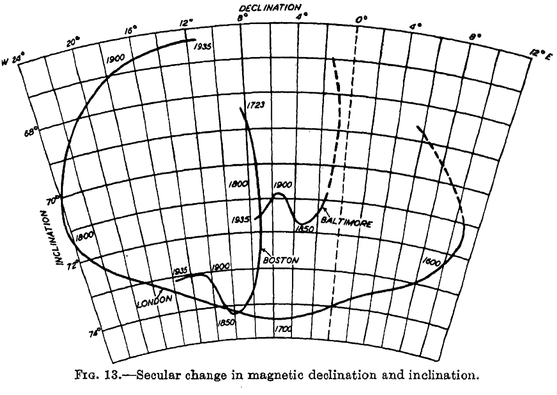


FIG. 13.—Secular change in magnetic declination and inclination.

the absolute measure of the magnetic intensity, or the strength of the magnetic field. It is really only since his time that serious research in secular variation has been possible. One hundred years would be scant time for the changes of the slow-moving forces to produce effects sufficient for the purpose even if a complete record of the changes for that period were at hand. But the record is fragmentary at best. What is known of secular variation prior to renewed activity in the study of the subject manifested by the establishment of a considerable number of permanent and well-equipped observatories during the closing years of the past and the opening years of the present century is in general limited to a few restricted regions or to scattered localities.

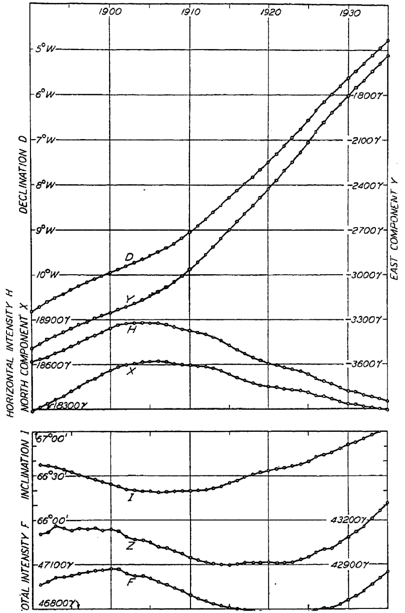


FIG. 14.—Annual means, magnetic elements and force components, Potsdam, Germany, 1890–1935 (*after Bartels*).

Whatever may be found to be the source of that magnetization, any changes affecting it must take into consideration the nature of simultaneous changes appearing over the entire surface of the planet. There is no known means of "remote control," no method by which, in a carefully equipped observatory or comfortable laboratory in an agreeable climate surrounded by the comforts of home, a competent staff of investigators can apply themselves to the solution of this problem.

Only a portion of the land surface of the Earth is peopled by nations whose intellectual and material equipment enables them to maintain magnetic surveys, and of the entire surface of the Earth but a minor fraction is of land. There are the backward lands, the jungles, and the deserts; there are the remote and all but inaccessible islands of the great oceans, and great expanses of the sea where no land is; there is the far frigid north and the frozen unknown of the farther south; such places must be included in a complete and homogeneous network of stations if a satisfactory picture of what is taking place is to be drawn. Such places cannot contribute the information of themselves; expeditions must be organized by those who are able to go and seek it—not once, but repeatedly—since it is not a condition but the changeableness of a condition which is sought. The phenomenon is not static but dynamic; it is not a still picture which we visualize once for all but a moving picture requiring repeated exposures, and each exposure meaning a long and arduous journey to parts where means of travel are primitive or entirely lacking, where oftentimes expensive expeditions must be organized and financed to secure pictures in the setting desired.

Often when a place has been revisited after an interval of years it is impossible to find and make a redetermination at the same position as that previously used, and a new point must be chosen. But as the time-changes sought are relatively small, and as local displacements often cause considerable differences due solely to peculiarities of the local geology, a new uncertainty is introduced to increase the difficulty of the task. Obviously the undertaking is too great for solution without the cooperation of scientific agencies of all countries. It is a satisfaction to record that there is a continually increasing number who are finding fruitful ways of contributing the details necessary to complete the picture.

As will be realized, the fascination—we may say romance—of the study of these data extends further to the efforts in their accumulation. Observational stations for the study of variations and perturbations must be located in out-of-the-way places even in populous countries to avoid those artificial disturbances arising from widespread use of electrical currents and devices. There is a lack of comfortable traveling conveniences in unexplored regions, despite the automobile, the airplane, and the dirigible, though these are all combining to lessen the old difficulties and the time required in getting about.

As already stated, the first magnetic-survey work at sea was between 1698 and 1700 on the *Paramour Pink.* Several voyages were made in the North and South Atlantic oceans, as far south as the 52° parallel. Halley embodied the results of his observations of the magnetic declination (the only element observed) in an isogonic chart for the epoch 1700—the prototype of later isogonic charts. Among subsequent expeditions

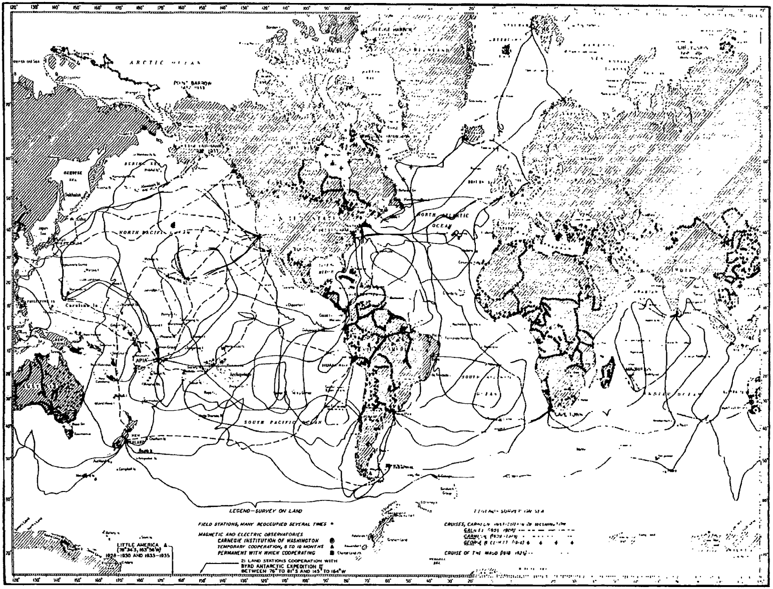

ARCTIC OCEAN
POINT BARROW
BERING SEA
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
SOUTH PACIFIC OCEAN
SOUTH ATLANTIC OCEAN
INDIAN OCEAN
APIA
HUANCAYO
CAPE TOWN
NEW ZEALAND
LEGEND—SURVEY ON LAND
FIELD STATIONS, MANY REOCCUPIED SEVERAL TIMES
MAGNETIC AND ELECTRIC OBSERVATORIES
CARNEGIE INSTITUTION OF WASHINGTON
TEMPORARY COOPERATION, 6 TO 18 MONTHS
PERMANENT WITH WHICH COOPERATING
LITTLE AMERICA
(78°34'S, 163°56'W)
1928–1930 AND 1933–1935
21 LAND STATIONS COOPERATION WITH
BYRD ANTARCTIC EXPEDITION II
BETWEEN 76° TO 81°S AND 145° TO 164°W
CRUISES, CARNEGIE INSTITUTION OF WASHINGTON
CRUISE OF THE MAUD

FIG. 15.—World magnetic survey, Carnegie Institution of Washington, 1905–38.

during which serious magnetic work was undertaken at sea may be mentioned those of the following vessels: *Erebus, Terror,* and *Pagoda,* 1840–45, chiefly in the southern oceans, attempted determinations of the three magnetic elements; *Novara,* Austrian frigate, 1857–60, obtained declination-observations while circumnavigating the globe; *Challenger,* 1872–76, two important expeditions; *Gazelle,* German vessel, 1874–76. Since the inauguration in 1903 of magnetic work on board the United States Coast and Geodetic Survey vessels, valuable series of observations have been secured along the Atlantic and Pacific coasts of the United States and in the Gulf of Mexico. Despite growing instrumental improvements, it is to be noted that because of the introduction of iron and steel in more modern vessels the early expeditions gave as good if not sometimes better data because of the varying effects of induced magnetic deviations in the later vessels.

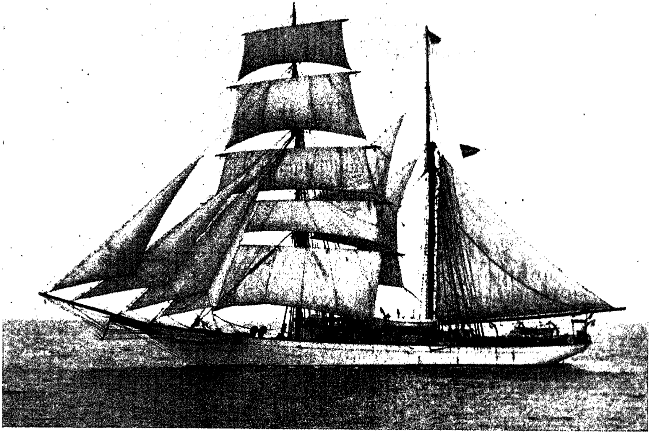


Fig. 16.—Magnetic-survey yacht *Carnegie* (mouth of Elbe River, 1928).

In this world magnetic survey to determine magnetic distribution and secular variation of the Earth's field the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has done much. This extended on land to those countries and regions where there were or are no established magnetic-survey organizations, or where existing agencies for one reason or another welcomed cooperation (see Fig. 15).

Thus, since 1905, almost 200 magnetic exploring expeditions to remote and little-explored regions were made. During 1905–29, also, an intensive magnetic survey of all oceanic areas was executed—for the first four years with the chartered brigantine *Galilee* in the Pacific (nearly 64,000 nautical miles), and during 1909–29 with the specially constructed, non-magnetic vessel, *Carnegie* (Fig. 16), in all oceans from 80° north to 60° south (nearly 298,000 nautical miles). The only other non-magnetic vessel, the *Cecilie*, did magnetic work in the Baltic Sea during 1925–26. The *Carnegie* was unfortunately destroyed by a gasoline explosion and fire in Apia Harbor, November 29, 1929, during her last and seventh world-wide cruise. Her work is soon to be resumed by a non-magnetic vessel named *Research* under construction by the British Admiralty. Several other nations, including Sweden and the U.S.S.R., also realizing the scientific and economic value of magnetic data at sea, are undertaking similar work. The number of magnetic stations of the Institution distributed on land and sea now totals nearly ten thousand. During the past decade over 300 of these have been reoccupied for secular-variation data.

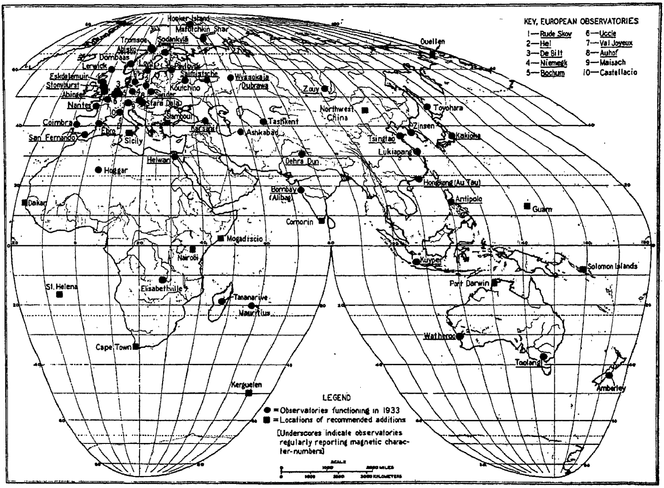


FIG. 17.—Established magnetic and electric observatories, Eastern Hemisphere, 1933, and recommended additions.

The distribution of existing magnetic observatories—so essential in the world magnetic survey—is shown by the black dots on Figures 17 and 18; the black squares on these charts indicate desirable locations of additional observatories to meet needs of the survey most satisfactorily. Figure 17, covering Europe, Asia, Australia, Africa, and the Indian Ocean, shows how great a majority of the observatories are in Europe. Figure 18 indicates the distribution of observatories in North and South America and in the Pacific Ocean. Such observatories and laboratories have, indeed, been established by forward-looking and scientific-minded nations, and they are an indispensable source of data which the solutions of magnetic questions require. Our own country, through the work of its Coast and Geodetic Survey, has contributed much especially in the past 35 years through its magnetic surveys of the United States, its territories, and coastal waters, and through the maintenance of five well-distributed observatories. The Carnegie Institution of Washington also established and maintains two magnetic observatories, the one near Watheroo, Western Australia, and the other near Huancayo, Peru (Fig. 19). The latter is uniquely located on the magnetic equator at an elevation above

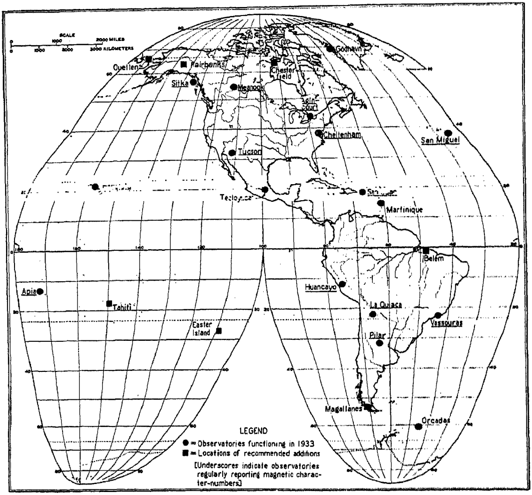


FIG. 18.—Established magnetic and electric observatories, Western Hemisphere, 1933, and recommended additions.

sea of 11,000 feet, while the former adds a much-needed station in the Southern Hemisphere.

An outstanding lack in the world magnetic survey is the paucity of observational data in the polar regions. Although occupying only about one-seventh of the Earth's surface, more data from these regions may modify considerably the results of the analyses so far made depending upon distribution of the magnetic field in the rest of the globe. The old challenge of the polar regions now having been met in the attainment of the two geographical poles, this portion of the world magnetic survey presents a really greater and equally intriguing demand which modern methods make feasible. In the Arctic as in the Antarctic the distribution of the magnetic field is unique because of the proximity of the magnetic poles and the changes in the magnetic field in these areas are great in comparatively small distances and in short intervals of time. Information regarding the compass-direction in the polar regions is based almost entirely on theories developed early in the first part of the nineteenth century by Gauss and Lamont. However, as observations in other parts of the world have also indicated, we must expect variations from theoretical values such as are caused by the presence of magnetic materials in the Earth's crust. For example, magnetic declinations determined by Stefansson during 1915–17, at 26 stations between latitude 74° and 80° north and longitude 98° and 124° west, showed differences in compass-direction from the values indicated on the best available magnetic charts then existing ranging from $-34°$ to $+21°$. On the *Maud* Expedition of Amundsen, 1918–25, it was found that near the new Siberian Islands the pointing of the compass-needle was 2° west of north, whereas the value on the latest chart for the corresponding position was indicated as 10°

FIG. 19.—Huancayo Magnetic Observatory, Peru (at 11,000 feet above sea-level).

east of north. The accumulation of additional reliable data in these regions has been greatly increased through the work of the International Polar Year Commission 1932–33. Twenty-six nations took part in that Commission's program.

VII. MOVEMENT OF SECULAR-VARIATION FOCI—ISOPORIC CHANGES

The magnetic-survey data being assembled, isomagnetic charts of the magnetic declination, inclination, and intensity may be prepared for various epochs upon which to base theoretical discussions. In succeeding epochs, because of secular variation, shifts of the isomagnetic lines have occurred. It is then possible to join by a new set of lines those points past which the isomagnetics—as those of compass-direction or declination—have made the same progress. Thus, for instance, those places at which the declination has changed at the rate of one minute of arc a year, let us say to the eastward, are joined together. The same is done for changes of two minutes, three minutes, and so on up to the maximum rate of change of about one-quarter degree, neglecting the immediate vicinity of the magnetic poles. Lines so drawn are called isopors, or lines of equal marching. Only recently has it been possible to attempt drawing such isopors for the whole world with any degree of detail (see, for example, the isopors of declination in Fig. 20). A splendid example of such isoporic charts is shown by Figure 21 as developed for various decades by the magnetic survey of the United States by the Coast and Geodetic Survey. The picture resulting from these preliminary charts has presented the whole question of secular variation in a new light and has raised questions of broadest geophysical significance.

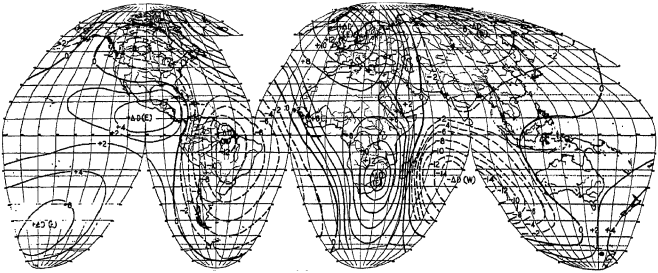


FIG. 20.—Isoporic chart for declination (lines of equal annual change), approximate epoch 1920–25.

While it may be true that the rotation of the Earth, with its magnetic field reaching out from it and surrounding it like a mantle constantly acted upon by radiations from the Sun and from the depth of space, subjects that field to a progressive precessional effect, what has long been suspected is becoming more and more apparent. A large part of the changes in the characteristics of the magnetic field has its origin, not from influences impressed upon it from without, but rather from silent and titanic forces ceaselessly at work deep within the Earth itself. It must have been something of this sort which was in the mind of the Norwegian

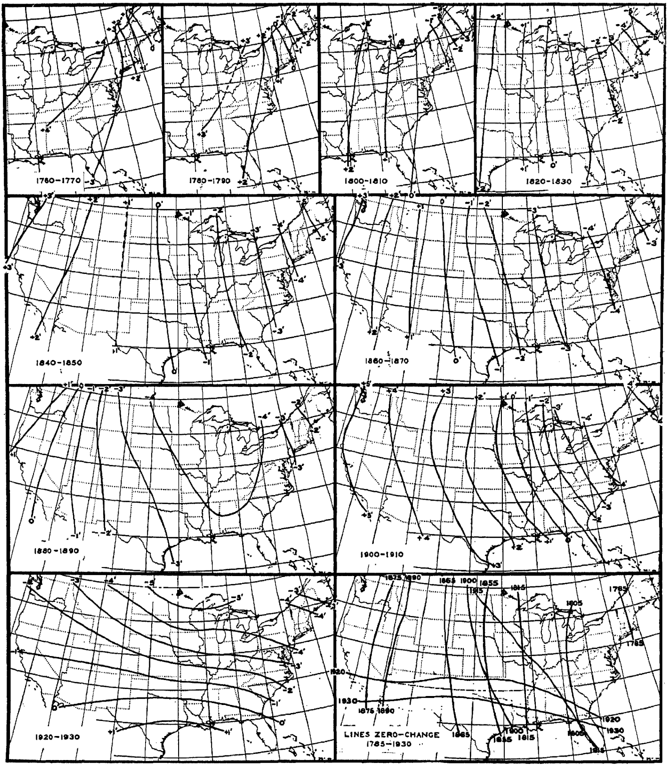


FIG. 21.—Declination-isopors for United States, 1760–1930, and lines of zero-change in declination, 1785–1930 (*after United States Coast and Geodetic Survey*).

magnetician of the past century when he said that "the variations of the magnetic needle are a mute language revealing to us the changes perpetually going on in the interior of the Earth." And when we see the rise and fall of the rate of the secular change, the slow expansion and then the gradual retraction of the areas within which there have been excessive alterations in any of the magnetic elements, we realize there are still active changes within the Earth's interior.

On the isoporic chart for declination (Fig. 20) drawn for the approximate epoch 1920–25, a line showing no change over the period of a year runs from Novaya Zemlya, off the northern coast of U.S.S.R., southward passing east of the Caspian Sea, thence continuing across Arabia and the island of Madagascar. East of this line the north end of the needle is pointing yearly farther west at a rate which increases slowly as the distance from the zero-line is increased, reaching a moderate maximum somewhere in eastern Siberia or Mongolia. The changes in the Indian Ocean are supposed to be larger than in Asia; this region is one where there are but few data available. However, to the west of that line of no annual change, over the greater part of Europe and extending somewhat into the Atlantic, there is a region of which we can speak with assurance, and one which presents a very interesting phenomenon. Numerous observatories have kept a continuous record of magnetic changes for nearly 40 years, some much longer, so that for that length of time the picture is for the most part complete. Proceeding westward from the Siberian border, we find the declination-isopors representing annual changes of one minute, two minutes, three minutes, and so on, packed quite closely together so that when we have reached Great Britain and the North Sea the annual rate of change in 1925 was nearly 13 minutes. The area having this large change is relatively small, so that the isopor takes the form of a small closed oval, surrounded by larger ovals successively representing the smaller changes. Along the northern part of Africa the changes are less rapid but in south Africa there is another focus of rapid change represented by concentric ovals on our isoporic chart.

But the foci of isopors are not permanent. The center of rapid change in western Europe has developed since the year 1900. If isopors are drawn for one-minute intervals, more than a dozen will be crossed at the present time in going from Ireland to the Ural mountains, whereas in 1905 scarcely more than one or two would have been crossed in the same distance. In 1932 the zero-isopor is as described at about 60° east longitude; in 1905 it was in central Siberia at about 90°. Thus, while these ovals of our picture are moving outward from a center somewhere north of Scotland, much as waves move in a pond from the spot where a stone has fallen into the water, the zero-line as a sort of shore-line against which these waves are beating has moved west to meet them. What the ultimate development of these figures will be we can only surmise, but there is reason to suppose that the dilation of these figures will be followed by a subsequent contraction. In eastern South America across a zero-isopor which passes from Labrador down the Atlantic past Cape Verde and St. Helena, there is a focus of opposite sign to those in Europe and South Africa, and the lines about this focus we know are moving inward. Do the lines move alternately inward and then outward, or do they continue to move inward until the focus disappears, perhaps to reappear elsewhere? We cannot answer these questions until time has supplied the necessary knowledge, or until some geophysical explanation has been found which will enable us to make a safe prediction.

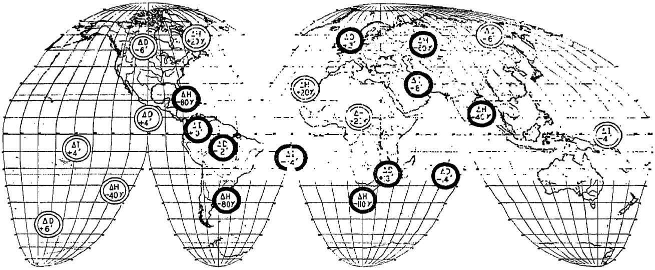


FIG. 22.—Distribution of foci of rapid annual change of magnetic declination, inclination, and horizontal intensity, approximate epoch 1920–1925.

The foci of isopors characteristic of the charts showing equal annual changes in declination are present also on the corresponding charts for the other elements. The distribution of these foci, shown by Figure 22, is noteworthy. They are practically all found in the hemisphere containing the great land-masses with the intervening Atlantic Ocean. Such foci as are found in the Pacific hemisphere are of but moderate intensity and not well defined. This fact is doubtless significant, though what the significance may be we can only conjecture. This relation of large and rapidly varying rates of change of the intensity and direction of the magnetic field to the surface structure of the Earth can scarcely be accidental; it is natural to suspect that there is a causal relationship existing between crustal or subcrustal movements and these magnetic manifestations. Perhaps there are changing mechanical stresses, or possibly a changing distribution of internal heat, which in turn affects the direction or magnitude of subterranean electric currents. The phenomenon certainly emphasizes the warning of Maxwell that we must not suppose the inner history of our planet has ended.

VIII. MAGNETIC ANOMALIES AND GEOLOGIC FEATURES

That irregularities of the distribution of the Earth's magnetic field over continental areas may bear definite relation to geologic features of the Earth's crust has been recognized for a long time. It is only in comparatively recent years that such magnetic data have been intensively considered as an aid in the determination of the character of geologic substructure. Accumulated observations make it possible to account for a considerable part of the Earth's field on the basis of a uniformly magnetized sphere. The difference between such a uniform or normal magnetization and that actually existing serves to bring out the general irregularities as a residual field (Fig. 23). The inhomogeneity of the Earth's outer crust or shell, perhaps 25 or more miles thick, gives rise to many regions of local magnetic disturbance. Thus magnetic ore-deposits are sometimes so great as to cause local poles and other irregularities of intensity twofold or even threefold the normal value in such regions. The anomalies at Kursk, U.S.S.R. (Fig. 24), at Berggiesshübel, Germany, and in New South Wales are three striking examples. The great anomaly in South Africa (Fig. 25) apparently retained for over 100 million years by the huge Pilansberg system of Paleozoic volcanic dykes has been recently examined by H. Gelletich. Fourteen vertical dykes, of horizontal widths between 65 and 350 feet and horizontal extent up to 100 miles, are found to be strongly magnetized in a direction opposite to the present-day magnetic field of the Earth. In this general region of South Africa the magnetic horizontal component of the Earth's field has decreased 16 per cent of its present value in a 30-year period!

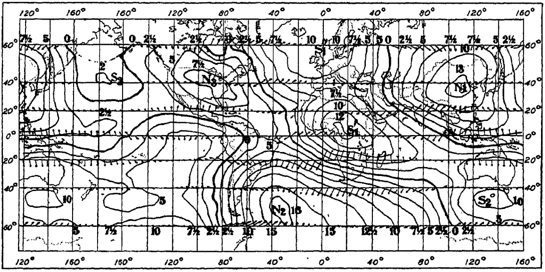


FIG. 23.—Earth's magnetic field after deducting uniform magnetization (*after Bauer*). Curved lines are the lines of equi-residual vertical force; arrows give direction and relative intensity of horizontal component of residual magnetic force; over regions about poles, N_1, N_2, and N_3, north end of magnet is attracted, while over regions of poles, S_1', S_1'', S_2, and S_3, south end is attracted; vertical intensities (large figures) are in units of second decimal, CGS.

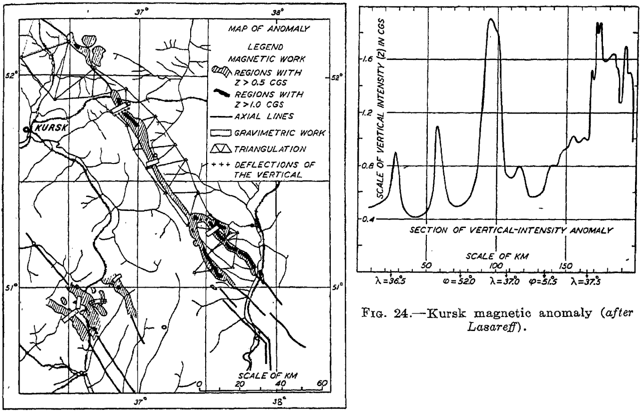


FIG. 24.—Kursk magnetic anomaly (*after Lasareff*).

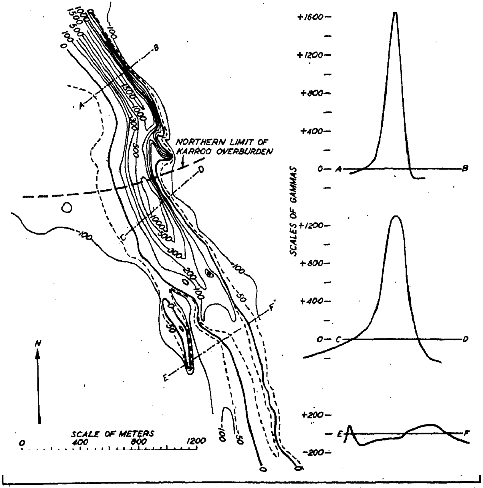


FIG. 25.—Magnetic anomaly of Pilansberg Dyke System, southern Transvaal, showing anomaly of vertical-intensity (*after Gelletich*).

The anomalous magnetic features thus observed over continental areas must have their counterparts in the great oceanic basins. We therefore may look confidently to such features as an aid in the study of oceanic structure. Indeed, observations made on isolated islands and island groups almost invariably indicate abnormal magnetic conditions. The magnetic survey of the oceans by the Carnegie Institution of Washington revealed such conditions at sea.

However, the application of magnetic-survey results to the investigation of crustal features of the ocean bottom depends upon the existence of a difference in substructural physical properties as well as on the magnitude of this difference. Here enters the magnetic susceptibility of rocks, some of which are strongly magnetic, as iron-ores and igneous and metamorphic rocks, and some weakly magnetic, as most sedimentary rocks. Here, then, one must think of the observed magnetic anomalies as a kind of general reconnaissance method to indicate areas for other more intensive geophysical studies. However, the magnetic method of approach lacks depth-control, and therefore the size of geologic features must increase in proportion to depth if we are to detect such features. Thus, unless the magnetic anomaly observed at sea is over shallow water or over deep water of enormous proportions, there may not be great hope of immediately deriving very exact information regarding particular areas of bottom substructure from distribution-data only as shown by isomagnetic maps.

The secular-variation phenomena afford a potential field of large value in the study of the Earth's crust. Investigators have long noted the apparent asymmetry and regularity of secular variation when attention is confined to a single station or to a small part of the Earth's surface such as western Europe—only one-hundredth of the Earth's surface. Considering, however, the actual observational data when the whole Earth is taken into account, secular variation is a regional phenomenon connected with a large geological structure—oceans and continents—of the deeper layers of the Earth's crust.

Isoporic foci in the Pacific Ocean are of but moderate intensity and not well defined. These relations to the surface structure of the Earth can be scarcely accidental; it is natural to suspect that there is a causal relation between crustal or subcrustal movements and conditions and these magnetic manifestations. As an example, attention may be called to the apparent diminution of the intensity of the Earth's magnetic field which is marked over oceanic areas, especially in the Southern Hemisphere. The interpretation of such data doubtless will be important in geophysical and geological research to advance understanding and interpretation of Earth phenomena.

For example, from observed earthquake-wave velocities and reflections for different regions and depths, Gutenberg estimates the crustal layer, which under most of the continental and water-covered continental structures is about 25 miles thick, is either lacking or quite thin under the Pacific Ocean, including possibly the Arctic region. Under the Atlantic and Indian oceans this layer is of appreciable depth. Thus under the Pacific Ocean the basic surface of the Earth's mantle is practically exposed. There then we may expect different geological and geophysical properties from those found elsewhere. Thus the observed longitudinal distribution of magnetic secular variation (Fig. 26) agrees with that of land areas (after Fisk, based upon data from 75° north to 65° south*)—as witness the

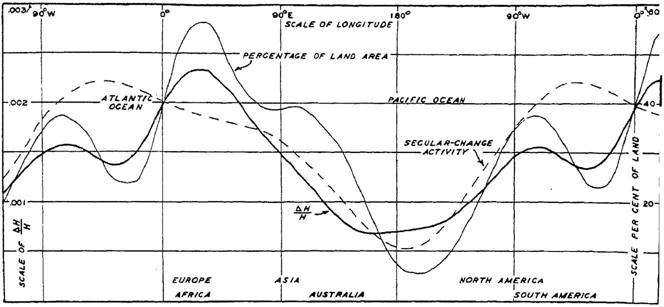


FIG. 26.—Variation with longitude of $\Delta H/H$ (annual change averaged without regard to sign), of distribution of proportion of land- and water-areas, and of secular-variation activity approximately determined by density of distribution of isoporic lines (*after Fisk*).

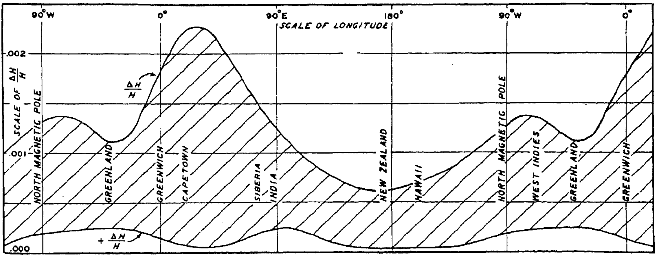


FIG. 27.—Longitudinal distribution of proportion of annual change, $(\Delta H/H)$, of horizontal intensity (*after Fisk*).

---

* In this graph showing distribution of annual change, $(\Delta H/H)$, of magnetic horizontal intensity, the lower curve represents the average positive values of $(\Delta H/H)$ in each lune between

moderate rates of annual change over the Pacific as compared with those over the Atlantic and adjoining continental areas. A definite control is necessary for a number of epochs to facilitate the investigation of causes producing and governing these progressive changes which, it appears, would be favored by accurate knowledge of their accelerations and distribution. The importance of the determination of secular variation over the oceans may be readily seen by a study of Figure 27.

There is an interesting possibility by which secular-variation information may be extended to times more remote than those for which observations exist. When lava cools and freezes following a volcanic outburst, it takes up a permanent magnetization dependent upon the orientation of the Earth's magnetic field at the time. This, because of small capacity for magnetization in the Earth's magnetic field after freezing, may remain practically constant. If this assumption be correct, the direction of the originally acquired permanent magnetization can be determined by tests in the laboratory, provided that every detail of the orientation of the mass tested is carefully noted and marked when it is removed. Samples of lava-flows of known data from Mount Etna back to 1284 have yielded fairly consistent data for magnetic declination and inclination, which apparently indicate a secular-variation period of about 750 years. Similar measurements have been made on lava produced by eruptions in the fourth century B.C.; however, results depending upon measurements of this kind must be used with caution.

Just as lavas cooling through the Curie-point in the presence of a magnetic field become magnetized in the direction of the field, so sediments containing microscopic magnetic particles also assume the direction of the prevailing magnetic field. This is in its truest sense "fossil" magnetization, for the magnetic field of the epoch of deposition is embedded in the sediment as surely as the organic remains of that epoch. Whether this fossil magnetism remains as a connate property of the rock or whether it is destroyed by subsequent events, even as organic fossils are sometimes destroyed, depends upon the postnatal experience of the sediment. In so far as it remains, it may supply a valuable record of the Earth's magnetism and an important clue to the history of the rock.

There is another possible source of such data, although certainly even more speculative than that from lava-flows. When vessels made of clay containing iron compounds are fired, they take on and retain a permanent magnetic condition and axis-direction depending upon their orientation in the Earth's field at the time of firing. These are negligibly influenced by later changes in the Earth's field. Determination of the direction of

---

the meridians, while the upper curve represents the numerical magnitude of the average negative values. Thus the shaded areas between the curves are measures of the excess of the negative over the positive annual change.

the magnetic axis may then give some idea of the inclination of the Earth's magnetic field at the time the vessel was made.

The measurement of the Earth's magnetism at great depths in the sea may now be possible through magnetic examination of the core-samples obtained from the ocean's bottom with the apparatus recently developed by C. S. Piggot. A method of magnetic measurement has been developed permitting tests of high sensitivity and accuracy without submitting such specimens to artificial magnetic fields. This method permits detection of the magnetic moment of a good steel magnet one mm long and one-hundredth mm in diameter.

Should such tests on cores show distinct differences in the direction of magnetization at various depths and that these differences are the result of differences in the Earth's field at the time the sediments were deposited, the core-samples may afford means to extend the past history of the Earth's magnetism. Through interrelating individual cores by similarities in their magnetism, it may be possible ultimately to date magnetically the rocks. This, too, would determine more accurately than observations on the surface the extent and character of regional magnetic anomalies below the ocean.

With improved knowledge of magnetic anomalies the question of interrelations with gravimetric anomalies and deep-focus earthquakes may be studied. It frequently is noted that gravimetric and magnetic anomalies occur in the same regions. Visser has recently noted an apparent relation that areas of deep-focus earthquakes are confined to the great regions of positive anomalies of magnetic vertical intensity around the Pacific Ocean. Vening Meinesz has found an excess of gravity in the oceans and a sudden decrease at the continental borders and has demonstrated these deviations of isostasy cannot be situated in the thin Earth's crust but must extend far into the plastic layers below. There must result current-systems in the Earth's interior, downward below the oceans and upward below the continents. The chart of isoporic foci and their motions with time certainly lend support to the idea indicating that the interior of the Earth is more mobile than the external layers, not only as a whole but regionally. Visser queries whether such interior currents may not convey material with special magnetic properties from the depths, accounting for positive disturbances at the crust. Possibly the anomalies of gravity and of terrestrial magnetism and the deep earthquakes have a common origin in current-systems in the inner Earth.

IX. SOLAR DIURNAL VARIATION

The second important time-change—the solar diurnal variation—in the Earth's magnetic field was discovered in 1722, at London, by a mechanician and clock-maker named Graham. It is stated that at

Louveau, Siam, in 1682, experiments in the presence of the King showed the compass-direction different on seven different days; probably these were made at different times of the day and thus were really the first observed indications of diurnal variation.

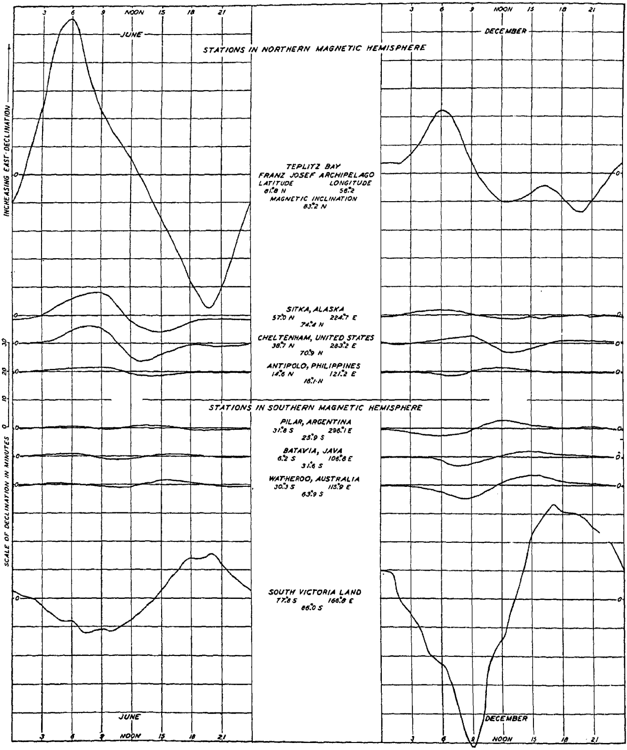


FIG. 28.—Diurnal variation or inequality in magnetic declination (curves show seasonal changes and modification in ranges for different latitudes).

The length of time required for collecting the necessary data for the study of the diurnal variation repeated day by day is more commensurable to man's lifetime, and that problem can therefore be studied at magnetic observatories within a reasonable time with much more detail than can the slow secular variation. Magnetic research has already yielded correspondingly more definite results in this aspect of the subject and has shown promising lines for future work. And while on one side the search for the explanation of the main part of the Earth's magnetic field and its secular variation is hampered by the fact that we know only one planet, namely, our own, and that we have to put up with those irregularities in its crust, that distribution of land and sea which we find upon it, we can on the other side collect data for the diurnal variation for very many days and utilize the natural differences in season, in magnetic disturbance, and in sunspot-numbers for testing theories and drawing conclusions.

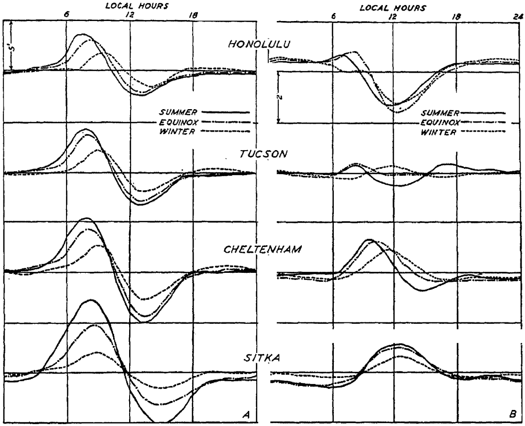


FIG. 29.—Diurnal variation of magnetic declination (*A*) and inclination (*B*) (*after United States Coast and Geodetic Survey*).

The diurnal variation changes with the season of the year, the range of this variation being greater in summer than in winter. As one goes from temperate zones to the frigid or to the torrid zones, these summer and winter variations present widely differing features. The extent to which such a variation varies throughout the year is readily seen by the graphs in Figure 28. It will be immediately apparent that diurnal variation in its main features progresses according to local mean time. Thus this variation is connected with the Earth's rotation and, as its major tendency follows the apparent motion of the Sun, it may be presumed that the Sun is an important factor in this daily phenomenon. This variation also is the first indication that the Earth's magnetism responds to outside influences which find their origin in solar activity and act upon the upper regions of the atmosphere. Figure 29 also indicates how this diurnal variation changes with season, the greatest ranges always occurring in the summer months.

In Washington the north end of the compass-needle on a magnetically quiet day starts swinging eastward, beginning with sunrise, continuing so until some time between 8 and 9 o'clock, when it swings rapidly toward the west until between 1 and 2 o'clock and then returns to its first position. The end of our giant two-mile needle would have an extreme motion in the course of daylight of about 10 to 15 feet; during the night hours its motion would be much slower and much smaller.

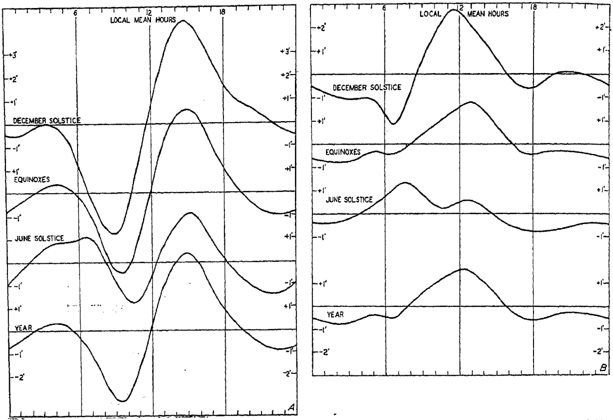


FIG. 30.—Mean seasonal and diurnal variations of magnetic declination, 1930: at Watheroo (*A*); at Huancayo (*B*).

The diurnal variation of declination at Watheroo in Western Australia for the year 1930 by seasons yields three curves (Fig. 30-*A*) exhibiting the "southern" type of variation which characterizes a magnetic observatory situated at about 30° south, where the focus of the external electrical current-system causing diurnal variation passes approximately overhead daily. The variation is greatest at the December solstice and least at the June solstice owing to the fact that the ionization produced by the Sun is greatest or least, respectively, over the Southern Hemisphere at those seasons. At Huancayo in Peru, on the magnetic equator, the corresponding graphs (Fig. 30-*B*) show the variation at the December solstice, when the Sun is actually south of Huancayo, is of the south temperate type, while when the Sun is over the Northern Hemisphere the variation is of the north equatorial type. This is an excellent indication of the changes which take place in the overhead current-system from season to season. Instead of moving northward or southward with the seasons as one might

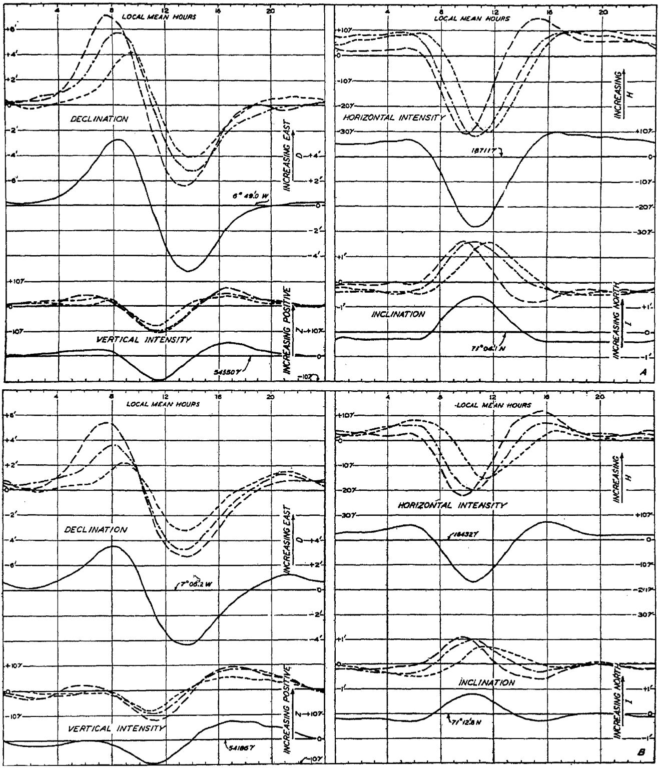


FIG. 31-*A*.—Curves of magnetic diurnal variation, Cheltenham, Maryland: (*A*) ten least-disturbed days, 1928, year of maximum in sunspot-cycle; (*B*) all days, 1933, year of minimum in sunspot-cycle. (Dotted line for December solstice; dashed line for June solstice; dot-dashed line for equinoxes.)

expect, this series of curves indicates that the southern current-circuit or the northern current-circuit expands according as the Sun is over the

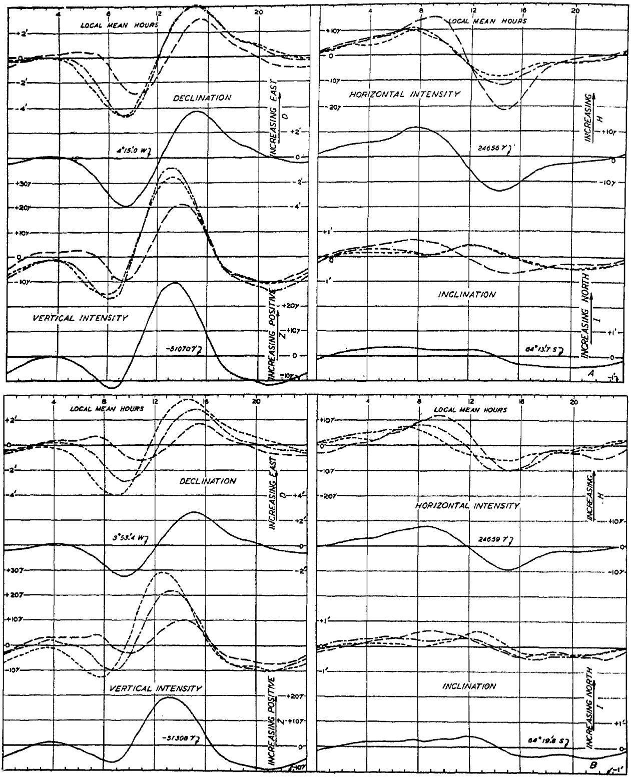


FIG. 31-*B*.—Curves of magnetic diurnal variation, Watheroo, Western Australia: (*A*) all days, 1928, year of maximum in sunspot-cycle; (*B*) all days, 1933, year of minimum in sunspot-cycle. (Dotted line for December solstice; dashed line for June solstice; dot-dashed line for equinoxes.)

Southern or Northern Hemisphere, so that during the northern summer Huancayo is included in the edge of the northern circuit while during the southern summer it falls well within the southern circuit. Figures 31-*A* and 31-*B* of results at Cheltenham and Watheroo also show the diurnal variations in the two hemispheres for years of maximum and minimum sunspot-activity. Similar phenomena are exhibited by the diurnal variations at Batavia and Apia, other observatories near the magnetic equator.

X. SMALLER PERIODIC VARIATIONS—LUNAR-DAY AND ANNUAL

Besides the solar diurnal variation there is another, small and quite systematic, namely, that associated with the Moon's position.

We have seen in several figures the average daily influence of the Sun on the magnetic force as revealed by the 24 average hourly mean values for a number of days giving the systematic changes in the course of a solar day, from midnight to midnight, that is, from one lower transit of the Sun to the next. In the same way, we can speak of a lunar day, reckoned from one lower transit of a Moon to the next. This interval is, on the average, 50 minutes longer than a solar day; for convenience, we divide it into 24 lunar hours of equal length. By combining the magnetic values for each corresponding lunar hour of a large number of days, we obtain the influence of the Moon on the Earth's magnetic field, that is, the lunar diurnal variation. The magnitude of the lunar variations is less than one-tenth of the solar and can be derived only by careful analysis from very many observations (Fig. 32-*A*).

While the lunar variation is too small to have practical interest for navigational purposes, it is very important for the investigation of the high layers of the atmosphere, where these magnetic variations are produced. The simple nature of the lunar variations, the double wave, indicates their tidal origin, that is, their relation to the same forces which cause the familiar regular rise and fall of the water in the ocean and which produce similar and even more regular movements in the atmosphere.

The full significance of the lunar variation is brought out if we calculate it separately for the different phases of the Moon, as has been done for data from Batavia and Greenwich. The resulting graphs (see Chapter VII, Fig. 8) are based on 63 years of observations, or over 180,000 hourly observations in the four summer months, May to August. The greater variation is during daylight, this effect of the tidal movements being enhanced by higher ionization, higher conductivity of the atmosphere. From our knowledge of the tidal movements and of the lunar magnetic variations, we can infer the change of ionization in the course of the solar day, and also the different physical state of the atmosphere in the different seasons, in different stages of the sunspot-cycle, and at different degrees of magnetic disturbance. The Batavia and Greenwich curves have opposite phase—Batavia a maximum at transit, Greenwich a minimum—because they are situated on opposite sides of the electric current-system in the upper atmosphere which produces them.

It is very likely that lunar variations originate in even higher layers of the atmosphere than the solar variations, because they are so extremely sensitive to changes in magnetic activity, as shown in Figure 32-*B*. In Batavia the lunar variation is just as regular on disturbed days as on quiet days, but the range is tenfold as great.

The location of an observatory is an important consideration affecting the evidence it provides for the study of this phenomenon. The Carnegie Institution's observatories at Watheroo and Huancayo are key stations in an investigation on lunar diurnal variations, the former being at the center of the current-system producing it and the latter being on the magnetic equator.

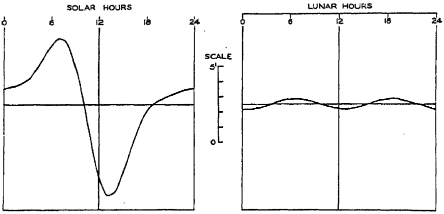


FIG. 32-*A*.—Solar and lunar diurnal variations, east magnetic declination in summer at Greenwich.

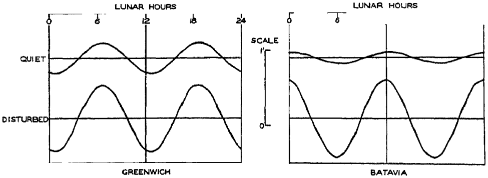


FIG. 32-*B*.—Lunar diurnal variation, east magnetic declination in summer on magnetically quiet and disturbed days.

The most conspicuous lunar effect found so far in any geophysical phenomenon—apart from the tidal oscillations of the sea—appears in the diurnal variation of magnetic horizontal intensity (that is, the force directing the compass) at Huancayo in the month of December and adjacent months. Figure 33 shows the solar and lunar diurnal variations separately, and Figure 34—somewhat schematized—the combined effect of Sun and Moon throughout half a month. The average of the combined solar plus lunar variation changes conspicuously. Moreover, there appears at certain phases of the Moon, in addition to the characteristic large upward swing before noon, a distinct downward swing before sunset. This downward swing, a purely lunar effect, appears quite plainly in the daily records, but only for a few days following full or new moon. A typical record of this is shown in Figure 35.

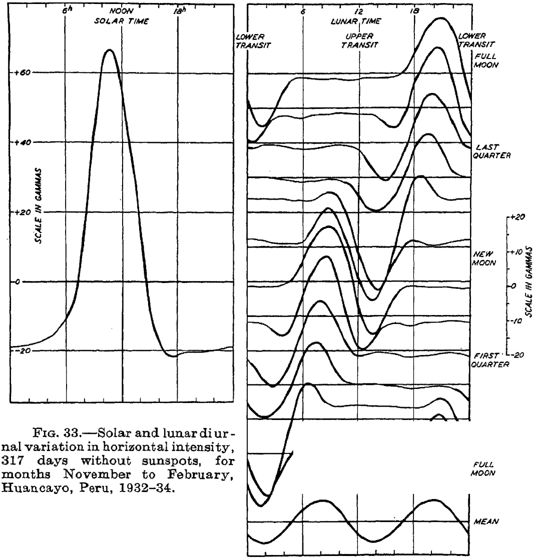


Fig. 33.—Solar and lunar diurnal variation in horizontal intensity, 317 days without sunspots, for months November to February, Huancayo, Peru, 1932–34.

When monthly values of compass-direction are corrected for the progressive secular change, they show a small variation with the year as a

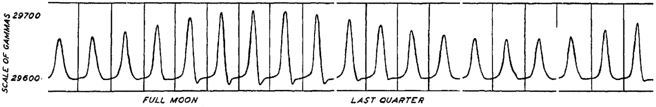


Fig. 34.—Schematic curve for solar plus lunar diurnal variation in horizontal intensity during half a month of December, Huancayo, Peru, sunspot-number zero, character-figure under 1.1.

period. This, known as the annual variation, is a cyclical change and should not be confused with the annual change which means the change in one year due to secular variation. This annual variation is a minute quantity—in noticeable contrast to the familiar change in meteorology—and for stations in North America shows a total range of about one minute of arc. Thus the ends of our giant compass-needle at Washington would oscillate because of this variation during the present year through little more than one foot. So far as investigated, the cause of this variation appears to be outside the Earth.

A study of the time-changes affecting the magnitude and direction of the forces controlling the movement of the compass-needle has shown us that both the Sun and the Moon exert a subtle influence over them, and it is but natural to infer that a similar influence emanates from the planets or from the distant stars. Such a possibility has not been overlooked but so far there is no positive evidence from available data that anything of that kind exists.

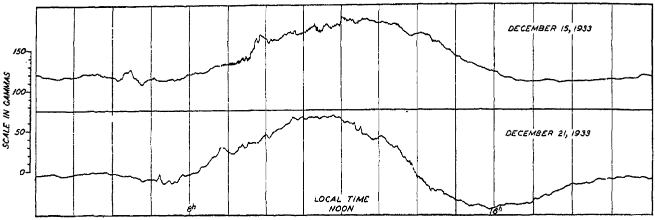


FIG. 35.—Photographic records of force directing compass on December 15 and 21, 1933, exhibiting combined solar and lunar diurnal variation before and after new Moon (December 16), Huancayo, Peru.

XI. IRREGULAR VARIATIONS AND MAGNETIC ACTIVITY

There are other time-changes of quasi-regular and of irregular types. These are associated with what we call the Earth's magnetic activity or, let us say, its general state of magnetic rest or magnetic unrest.

This magnetic activity at a given station, during any interval, may be defined as a measure for the frequency and intensity of marked irregular deviations—magnetic storms, for example—from the normal diurnal variation, in that interval. There are many ways in which such a definition may be numerically expressed. The simplest and now most generally used is the international characterization. In this every observatory, from inspection of the character of its photographic records, assigns to each 24 hours between successive Greenwich midnights a "character-figure" on a scale 0-1-2. The character "0" applies to quiet, "1" to moderately disturbed, and "2" to greatly disturbed days. The adopted daily values are the averages for all collaborating observatories, the

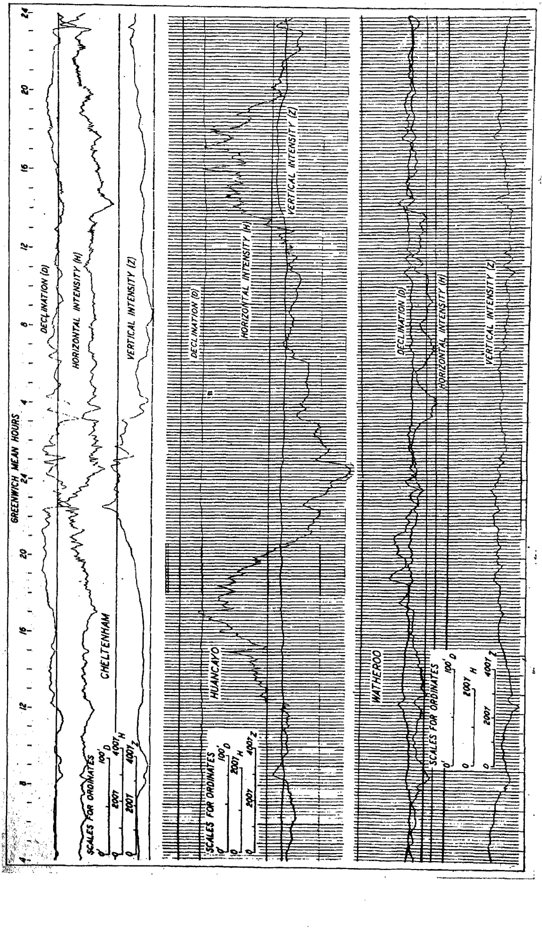


FIG. 36.—Variations in Earth's magnetic field during mild magnetic storm, April 21–22, 1936.

number of which increased from 30, when this measure was begun in 1906, to 53 in 1938.

A more detailed method of measuring activity is that called the *u*-measure. This depends upon the interdiurnal variability, that is, the average difference regardless of sign, in the force directing the compass between successive daily means.

During days of character 2 our giant two-mile needle will have violent oscillations, causing its north end to move through as much as 100 feet in Washington. At stations in polar regions, these disturbances are more violent because of the proximity of the magnetic poles. Actual records for Arctic stations have been obtained at times which would indicate that the north end of our giant needle would have shifted during such disturbance 20° to 30°—equivalent to a total displacement of its end through distances of about 2,000 to 3,000 feet. When it is borne in mind that such deflections may occur in a few minutes of time, the agitation of the Earth's field during such disturbances is readily realized. All intermediate stages between very quiet and extremely disturbed conditions exist.

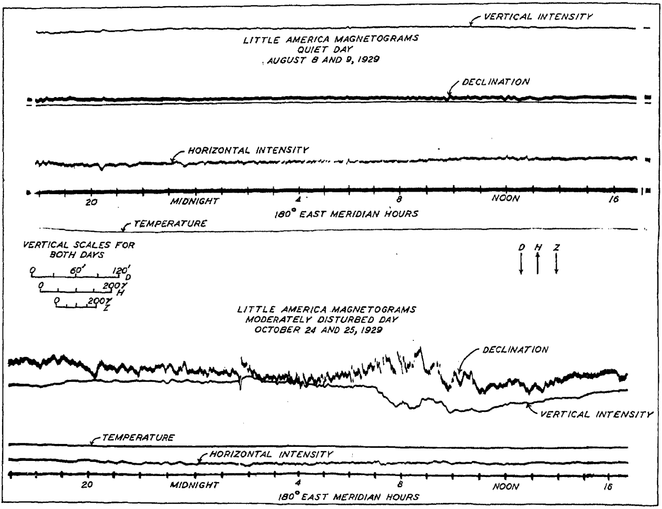


FIG. 37.—Typical magnetograms on quiet and moderately disturbed days at a polar station.

Magnetic disturbances may be classified as (1) world-wide magnetic storms, simultaneous over the Earth and primarily due to changes in the electric conditions outside the Earth, and (2) smaller disturbances restricted to parts of the globe and with center of field of action at times stationary but generally moving from place to place. Storms of the first type may follow comparatively quiet or normal conditions and are often initiated by a sudden sharp shift—a "sudden commencement"—simultaneous, within a minute of time, at all observatories. A tendency to oscillation and continued unrest during intervals varying from ten hours to several days is one of the outstanding features of such storms. Figure 36 reproduces the records of disturbed days at the Cheltenham, Huancayo, and Watheroo observatories, April 21–22, 1936. Figure 37 shows quiet and moderately disturbed records obtained in 1929 at Little America, at the temporary magnetic observatory of the First Byrd Antarctic Expedition.

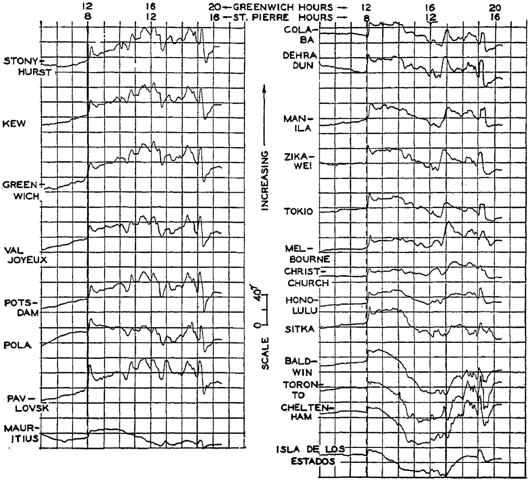


FIG. 38.—Magnetic disturbance in horizontal intensity, Mont Pelée eruption, May 8, 1902.

Figure 38 reproduces records of the compass-directing force at 21 observatories during a magnetic storm in May, 1902, which began at the time of the great volcanic outburst of Mont Pelée, Martinique; this coincidence was noted by L. A. Bauer, but it remains, so far, the only one of its kind ever observed.

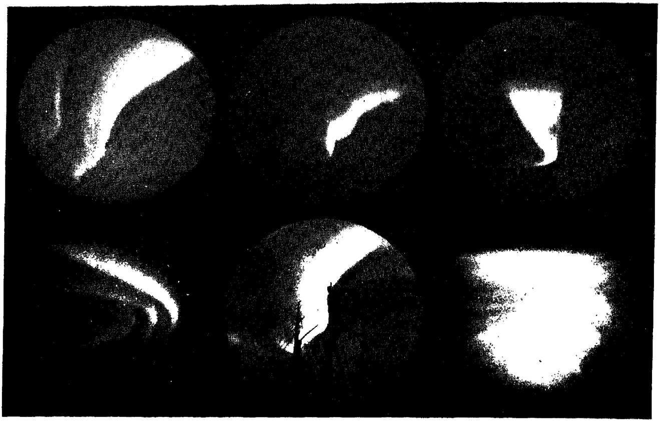


FIG. 39-*A*.—Typical auroral curtains and corona photographed in Arctic Sea off north coast of Siberia, 1919–23 (*after Dahl, Malmgren, and Sverdrup*).

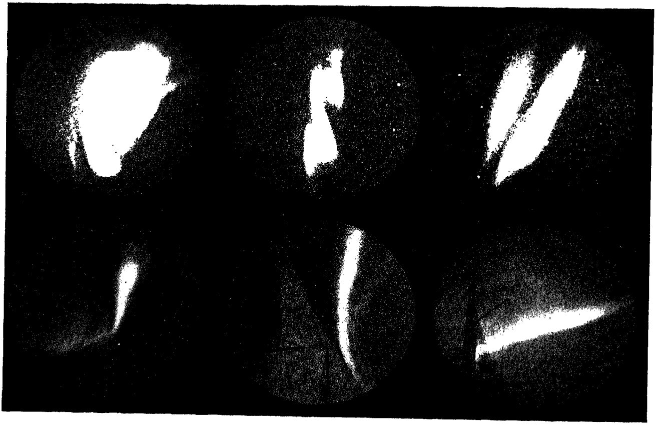


FIG. 39-*B*.—Typical auroral arches, corkscrew-shaped curtains, and bands photographed in Arctic Sea off north coast of Siberia, 1918–24 (*after Dahl, Malmgren, and Sverdrup*).

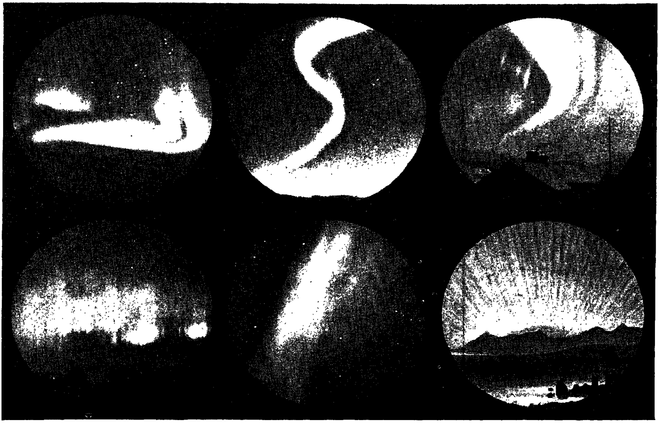


FIG. 39-*C*.—Typical auroral bands and rays, first five photographed in Canada and Norway, 1910–33 (*Davies and Störmer*) and last one from drawing in Norway published 1856 (*Müller*).

The second, more local type of transient magnetic disturbances is usually represented by a rather slowly developing "bay" on the record extending over half an hour or somewhat more.

Thus disturbed or quiet magnetic conditions nearly always affect the whole Earth simultaneously. The possibility of any connection between disturbances of the Earth's magnetic field and the weather is excluded since weather is so distinctly local and so different all over the world. But polar lights—the auroras—are always seen in polar regions when magnetic storms occur. Figures 39-*A*, 39-*B*, and 39-*C* show photographs of auroral displays of several types. The last auroral reproduction of Figure 39-*C* is of interest as illustrating the careful observation of such phenomena by our predecessors—it was sketched in Norway about 1856 and is reproduced from J. Müller's cosmic atlas published in that year.

Minute particles in varying numbers are coming continually from the Sun. Once within the Earth's magnetic field, those electrified corpuscles, which are entrapped by the outermost lines of magnetic force, travel in spiral paths around them. They get deeper down in our atmosphere in the polar regions, where the magnetic-force lines are steepest. When the particles pass through the atmosphere, they cause the air to glow by their impact, and produce brilliant polar-light displays. From simultaneous photographs of aurora, taken at two stations a known distance apart, it has been found that polar-light beams generally do not come closer to the Earth's surface than about 50 miles; some come no closer than 300 miles or more. Since the height of polar lights is in no case less than 50 miles above the ground, the conclusion is drawn that the magnetic variations and disturbances also have their origin in electrical phenomena taking place at least at greater heights in the atmosphere. This has been confirmed in every respect and the study of the magnetic variations is one of our main sources of information about the constitution of and the phenomena in these outermost and inaccessible regions of the atmosphere.

It is therefore of interest to study the electricity existing in the atmosphere a hundred miles or more above our heads. This is the electrification which is responsible for guiding radio waves round the curved surface of the Earth. Because we are unable to visit these great altitudes, we have to study the electrification of the upper atmosphere from our position here on the surface of the Earth. This is rather like being blindfolded and taken to the foot of a hill and then told to make a survey of the hill without walking up it. We could attack such a problem by rolling a ball up the slope and finding how long it took the ball to roll back to us. The more energetically the ball is started off, the farther up the slope it would go before beginning to roll back. If it is started off too energetically, it would roll right over the top of the hill and fail to return. By this means an excellent idea would be formed of the height of the hill. In surveying the electrification of the Earth's upper atmosphere, it is possible in a similar way to deduce the greatest density of electricity in the atmosphere by finding how rapidly a radio wave must be made to vibrate before it can penetrate the electrification and pass out into space. This is accomplished by automatic records of the way in which the time-delay of radio echoes from the upper atmosphere varies with the frequency of vibration of the waves. There is a frequency beyond which no echo is obtained and its square is proportional to the greatest density of electricity in the atmosphere. This type of research and correlations of ionospheric conditions with magnetic phenomena are described in Chapter IX.

Another type of irregular disturbance is that known as micropulsations, first noted by Eschenhagen and which appear to be of about the same magnitude at different locations on the Earth. These are of very short periods, such as 5 to 15 sec of time. On the other hand, there are recorded at observatories in regions of comparatively limited area a giant type of pulsation with periods of as much as one and one-half to two minutes of time and ranges from 10 to 20 times as great. At the present time there is apparently such an area near Scandinavia. Figure 40 shows records of giant pulsations obtained September 10 and 12, 1930, at Abisko, Swedish Lapland, and September 12, 1930, and September 19, 1931, at Tromsö, Norway. Tromsö is somewhat over 90 miles north of Abisko.

At two other observatories 215 and 370 miles, respectively, from Abisko, the ranges recorded were considerably reduced, while they were found to be very minute or negligible at observatories distant about 1,000 miles or more. They may reasonably be ascribed to peculiar currents then prevailing in the atmosphere above the northern part of Scandinavia. Less regular fluctuations of the force directing the compass are conspicuous features in the large daytime increase recorded at Huancayo (see Fig. 36).

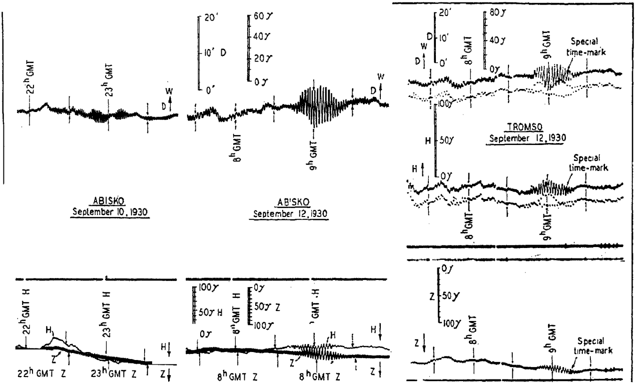


FIG. 40.—Records of giant magnetic pulsations.

XII. SOLAR ACTIVITY AND EARTH'S MAGNETIC STATE

It was ably demonstrated in 1908 by Hale at the Mt. Wilson Observatory of the Carnegie Institution that the Sun has a magnetic field of intensity perhaps 50 times that of the Earth. But a field of that intensity is far too weak to make its magnetic influence felt at the Earth, 93,000,000 miles distant. It is much more probable that solar influences on the Earth's magnetism are connected with enormous streams or clouds of particles, atoms, ions, and electrons ejected from the active regions of the Sun, which travel through space and from time to time reach the Earth after one or two days and impinge upon its atmosphere, causing magnetic storms, which often disturb electrical communications. These particles, like certain wave-radiations mentioned above, do not reach the Earth's surface but are stopped by the air before they come lower than 50 miles and cause indirectly observed effects such as electric currents in the air and in the Earth. Thus one may conceive magnetic disturbance-features as the result of "messages from space."

The regular daily magnetic variation apparently is the effect of other radiations from the Sun, which travel with the velocity of light and are absorbed in the highest levels of the air and which make these layers electrically conducting. These conclusions drawn many years ago from magnetic observations became more important after the invention of wireless telegraphy, because by them we may explain why wireless waves are bent around the Earth along and below these conducting layers. A striking confirmation of these interrelations has been found recently in the study of certain types of radio fade-outs—interruptions in short-wave radio transmission lasting from a few minutes to an hour. They occur only in the sunlit hemisphere of the globe and in so many cases simultaneously with sudden solar flares—bright gaseous eruptions in restricted areas of the Sun, seen in the spectrohelioscope—and with small but conspicuous terrestrial-magnetic changes that the physical relationship appears certain. Figure 41 shows such an occurrence.

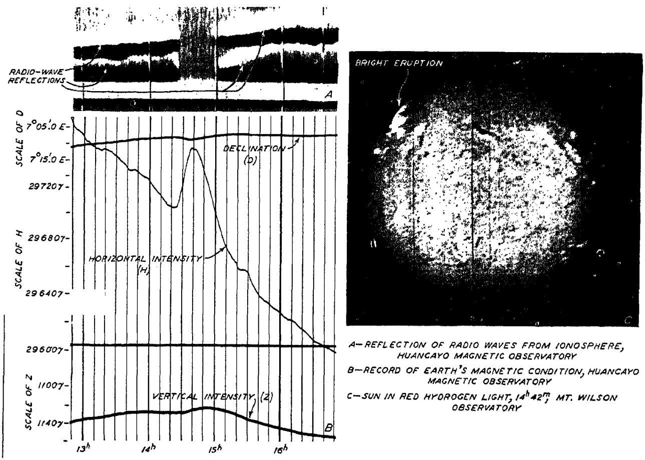


FIG. 41.—Changes in Earth's magnetism and cessation of radio reflections from ionosphere accompanying bright eruption in solar chromosphere, August 28, 1937.

The range of diurnal variation varies with magnetic character—a feature brought out in Figure 42. Statistical studies, which tend to smooth the violent irregular fluctuations, have led to the identification of three main features of a magnetic storm. These are: (1) An everywhere similar but unequally large general course according to universal time; (2) a superposed diurnal movement according to local time, differing characteristically from the ordinary diurnal variation on quiet days; and (3) an after-effect, which gradually subsides in the recovery during the days after a storm.

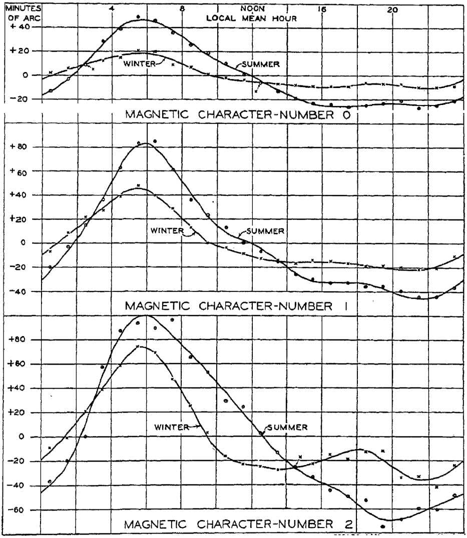


FIG. 42.—Correlation between daily variation of compass-direction and magnetic activity at Cape Chelyuskin, Siberia, October, 1918, to September, 1919.

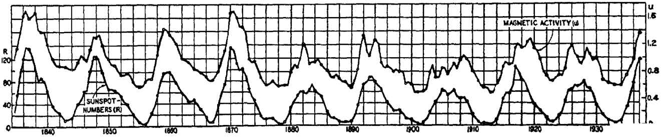


FIG. 43.—Annual means of magnetic activity and sunspot-numbers, 1835–1937.

Magnetic activity provides one of the means of determining another time-change, namely, that of an 11-year cycle apparently agreeing with the well-known cycle in sunspot-frequency (Fig. 43). Latest investigations have shown, however, that solar activity as indicated in its reflected effect in the magnetic field is not completely or always represented by sunspottedness or other phenomena which astrophysicists observe on the Sun's surface; magnetic observations apparently reveal distinct solar influences of another kind and add in this way to our knowledge of solar physics.

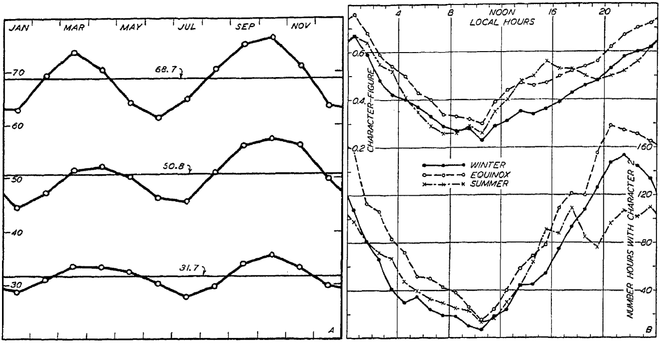
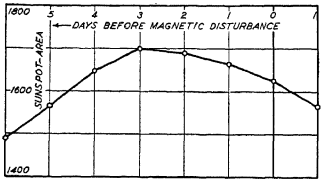
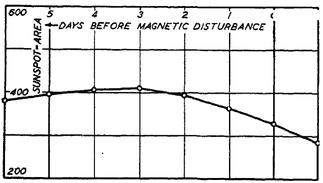


FIG. 44.—(*A*) Annual variation of magnetic activity, 1872–1930, arranged according to high, average, and low activities; (*B*) diurnal variation of magnetic character, Kew Observatory, 1913–1923 (*after J. M. Stagg*).



YEARS WITH MANY SUNSPOTS



YEARS WITH FEW SUNSPOTS

FIG. 45.—Sunspot-areas before magnetically disturbed days (*after J. M. Stagg*).

As the Earth revolves about the Sun during the year, there are corresponding fluctuations in magnetic activity, the maximum or crest occurring during the equinoctial months of March and September, and the minimum or trough in the solstitial months of June and December. This annual variation of magnetic activity, shown by Figure 44-*A*, was deduced from the examination of 59 years of observations, 1872–1930, at a number of observatories. The graphs result from grouping the data in thirds according to high, average, and low activity. Figure 44-*B* shows diurnal variation of magnetic character at Kew Observatory during 1913–23. In Figure 45 we have other evidence of the relation between solar activity and magnetic activity.

Another time-change related to magnetic disturbances is shown by Figure 46, for an interval chosen at random, the consecutive averages of magnetic force over 24-hour intervals centered at 0^h, 6^h, 12^h, and 18^h Greenwich mean time for three widely separated stations—Seddin, near Potsdam, Germany; Huancayo, Peru; Watheroo, Western Australia.

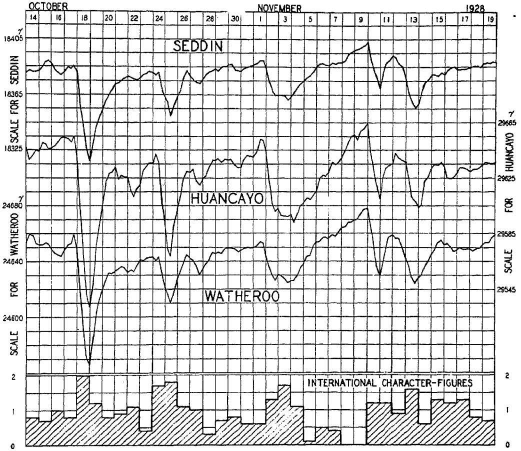


Fig. 46.—Typical depression following magnetic disturbances, and international magnetic character-figures, October 14 to November 19, 1928.

The three curves are strikingly similar showing typical depression during a disturbance followed by gradual recovery to normal value afterward. Obviously the *u*-measure which is derived from such systematic changes must be representative of the world-wide magnetic activity.

Cosmic rays, penetrating from the depths of cosmic space to the surface of the Earth, are deflected by the magnetic field of the Earth. Figure 47 shows a significant world-wide decrease in cosmic-ray intensity simultaneous with a magnetic storm in April, 1937.

XIII. CONCLUSION

The following conclusions have been drawn from the extended mathematical analyses of magnetic-survey data for mean epochs 1842, 1882, and 1922. The main cause of the secular variation arises from a system of forces embedded in the Earth. Secular variation is caused not only by a change in direction of magnetization but likewise by a change in the intensity of magnetization. The average annual decreases in magnetic force have been larger for the Southern, or water, Hemisphere than for the Northern, or land, Hemisphere, while the average equivalent intensity of magnetization over continental areas is somewhat larger than that over oceanic areas. There appears to be a small decrease each year in magnetization—approximately one fifteen-hundredth part. The Earth's total magnetic field at any one time is apparently attributable to the extent of about 94 per cent to an internal magnetic system and to an extent of about 6 per cent to external systems. The amount ascribed to external systems is, however, likely to appear still too large because of our imperfect knowledge of the Earth's field in polar regions; it would probably be reduced to about one per cent if the actual field were known and analyzed.

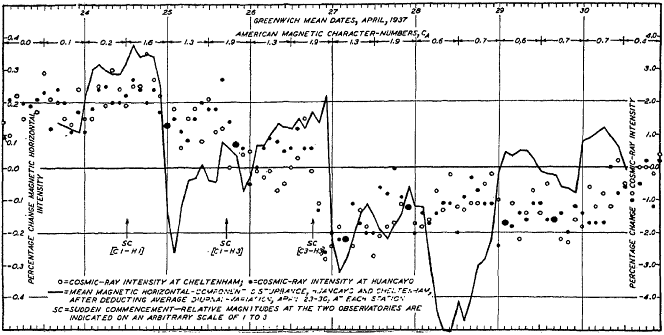


FIG. 47.—Bihourly departures expressed in percentage of absolute values for cosmic-ray intensity and for disturbance of magnetic horizontal component, April 23-30, 1937, Huancayo and Cheltenham magnetic observatories.

This complexity of the magnetic field of the Earth and its time-change phenomena has baffled attempts at theoretical explanations or hypotheses although long the field of able and enthusiastic investigators. We may hardly hope in our time to lay down a general theory which will explain the multitude of observed facts or permit us to foretell with any precision future changes. Despite this, magnetic observations have already added materially to our knowledge of the Earth's interior, particularly to some of the geological features of its crust. Thus secular-variation changes within the crust indicate an interior more mobile than the exterior layers, not only as a whole but regionally. Even more definite and promising are the results of those magnetic researches which give us also additional information regarding the high atmosphere above the Earth.

We must continue looking to observations and to their discussion for further advance in knowledge of the causes and laws governing the Earth's magnetic phenomena, as well as to provide means for the testing of theories. The rapid developments in physics, particularly in nuclear physics during the past decade—ionization, radioactivity, radio-wave transmission, and high-vacuum electrical research—will permit speculations on the origin and changes of the Earth's magnetic field, which must materially advance fundamental conceptions of the nature and constitution of matter.

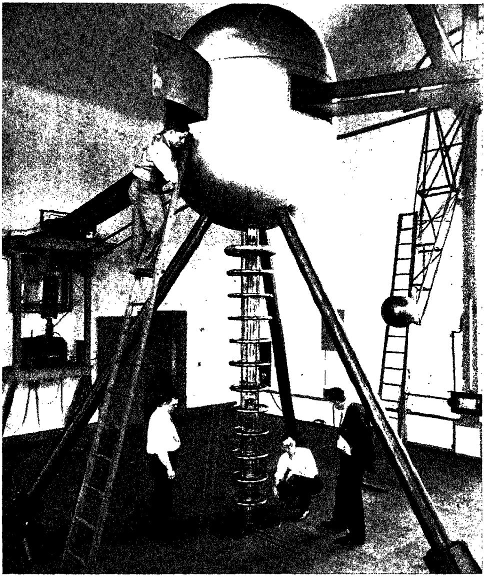


FIG. 48.—1,200,000-volt electrostatic generator, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Reference has been made to our approach by radio-wave propagation to a solution of the complex phenomena of the Earth's magnetic and electric field. A second active, and equally promising, approach in the laboratory is through the atomic nucleus. All the actions and reactions in the world of physical things may be expressions of three fundamental forces, namely, gravitational, electromagnetic, and nuclear. Perhaps all three may ultimately be reduced to different aspects of some all-pervading, all-inclusive type. Perhaps some obscure atomic effect of the extremely high pressures at the centers of such bodies as the Earth and the Sun may be the cause of their magnetization.

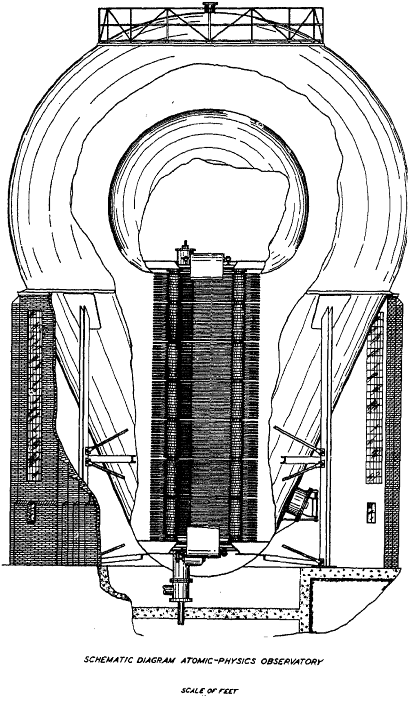


FIG. 49.—Schematic diagram Atomic Physics Observatory, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Therefore, there has been under way for some years experimental studies of nuclear physics particularly through the use of high voltages. The cyclotron is one form of apparatus extensively used in this field. At the Department of Terrestrial Magnetism, Carnegie Institution of Washington, a second type has been developed, namely, the electrostatic generator, which offers certain advantages over the cyclotron. This generator—constructed and improved after original designs of Professor Van de Graaff of the Massachusetts Institute of Technology—giving voltages up to one and one-quarter million, is illustrated in Figure 48. The Department planned in 1935 an electrostatic equipment capable of reaching five to eight million volts. It is shown schematically in

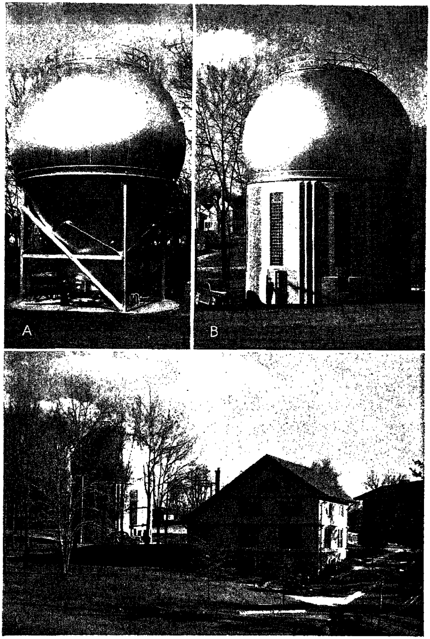


Fig. 50.—Atomic Physics Observatory, Department of Terrestrial Magnetism, Carnegie Institution of Washington: (*A*) in construction, (*B*) completed, (*C*) general view with laboratory housing 1,200,000-volt generator.

Figure 49. This equipment and its housing were completed in 1938. The necessary steel pressure tank, 55 feet high and 37½ feet in diameter at its greatest section, in which the generator is to be operated under 50- to 60-pounds gage-pressure, is shown in Figure 50-*A* during construction. Figure 50-*C* is a view of the completed Atomic Physics Observatory—observatory since we look to the infinitely small as our astronomical colleagues look to the infinitely large in space; the Observatory is to the left in the background and the laboratory housing the present equipment is to the right in the foreground.

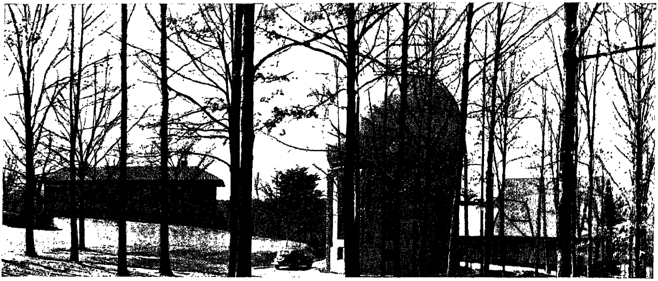


FIG. 51.—Laboratories and Atomic Physics Observatory, Department of Terrestrial Magnetism, Carnegie Institution of Washington.

Work in nuclear physics, dealing with fundamental conceptions of the nature and constitution of matter, must contribute further to the knowledge of the origin and to laws governing the complexities of the Earth's magnetic field so far found through the world magnetic survey.

CHAPTER II

MAGNETIC INSTRUMENTS

H. F. JOHNSTON AND J. A. FLEMING

Department of Terrestrial Magnetism, Carnegie Institution of Washington

H. E. McCOMB

United States Coast and Geodetic Survey

I. INSTRUMENTAL REQUIREMENTS

The complete determination of the Earth's magnetic field at any point requires knowledge of the direction and intensity of the field at that point. The elements which define the magnetic field at the given point are indicated schematically in Figure 1.

(1) DECLINATION

The magnetic meridian at any place is the vertical plane containing a line of force of the Earth's magnetic field at that place. The true or geographical meridian at the place is the vertical plane which passes through the Earth's geographical poles. The angle between these two planes is known as the magnetic declination, D. It is often called the variation of the compass or simply "variation," particularly by the mariner. The true meridian is ascertained by observation on the Sun or a star [122] and the magnetic meridian by observing the direction of a magnet free to turn about a vertical axis. The magnet may rest on a pivot as in an ordinary compass, or it may be suspended by a fine fiber as in a magnetometer. In the latter case the magnet, if solid, is provided with a plane mirror, or one end of the magnet is polished to a mirror surface for observing its direction accurately by a telescope and scale. If the magnet is hollow, a collimating lens is mounted in one end and in the other a scale engraved on a glass diaphragm. If precisely constructed, the line through the center of the scale and the optical center of the collimating lens defines the geometrical axis of the magnet. Since the geometrical and magnetic axes rarely coincide, it is necessary, in accurate determinations of the magnetic meridian, to make observations first with the magnet erect and then with the magnet rotated 180° in its suspension. The magnetic meridian is the mean of the directions taken by the geometric axis in these two observations.

(2) INCLINATION OR DIP

The magnetic inclination or dip, I, is the angle which the line of force in the magnetic meridian makes with the horizontal plane at the place of observation. It is measured with a dip-circle or an earth-inductor.

In a dip-circle, a magnetic needle is so mounted that it is free to turn about a horizontal axis. The axis about which a dip-needle rotates rarely passes through the center of gravity of the needle; it is therefore necessary, in obtaining an accurate value of the inclination, to observe with the face of the needle both to the east and to the west in the magnetic meridional plane and to observe with the polarity of the needle reversed, taking the mean of all observations as an accurate value.

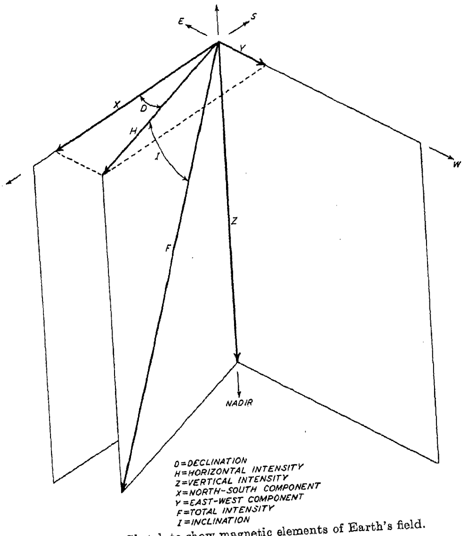


FIG. 1.—Sketch to show magnetic elements of Earth's field.

The operation of the earth-inductor—a more precise instrument than the dip-circle—depends upon the fact that, when a closed coil of wire is rotated in a magnetic field so that the number of lines of magnetic force through the coil changes, an electric current is induced in the windings of the coil. The coil of the earth-inductor rotates about an axis in the plane of the coil. To determine the inclination it is necessary only to find that position of the axis of rotation of the coil in which no current flows on rotation of the coil with its axis of rotation in the magnetic meridian. The axis of rotation of the coil is then parallel to the lines of force passing through the coil. The axis of rotation of the coil is first placed in the magnetic meridian by means of a specially designed magnetic compass. The inclination of the axis is then changed until, upon rotation of the coil about its axis, no current is generated in the coil as indicated by a sensitive galvanometer placed in the circuit. The inclination is then read directly on a vertical circle rigidly attached to the yoke which carries the coil. Observations are made with the vertical circle both to the east and to the west, the precise value of the inclination being the mean of these two observations. In the more elaborate earth-inductors the coil is provided with a special level so that readings of the vertical circle may be made with the axis of the coil vertical.

(3) INTENSITY

The intensity or strength of a magnetic field at a given point is defined as the force which it exerts upon a unit magnetic pole placed at that point. The unit magnetic pole is one which repels an equal and like magnetic pole with a force of one dyne in vacuo when the distance between them is one cm. The unit of magnetic intensity is called the oersted. Since the permeability of air is almost unity, the density of magnetic flux and the magnetic intensity are almost equal. In practice the unit of magnetic intensity is frequently called the gauss, indicated by capital gamma (Γ). Since, in most places on the Earth's surface, the intensity of the Earth's magnetic field is less than one oersted, it is more convenient to use the lower case gamma (γ), which is 0.00001 oersted. In early determinations of the Earth's field the British foot-grain-second unit was used. Values expressed in this older system must be multiplied by the factor 0.04618 to convert them into the CGS system.

The total intensity, F, of the Earth's field is usually determined by measuring its horizontal component, H, and its inclination, I, as described above, and then by computation from the relationship

$$F = H \sec I \tag{1}$$

The values D, H, and I are the three magnetic elements usually observed. Their relations to the north component, X, to the east component, Y, and to the vertical component, Z, are given by equations (1*a*) to (1*c*).

$$X = H \cos D \tag{1a}$$

$$Y = H \sin D \tag{1b}$$

$$Z = H \tan I \tag{1c}$$

It is general practice to refer all values to the north-seeking end of the needle and to consider east declination, north inclination, horizontal component, and vertical component directed downward as positive [+]. Small variations of the three elements, obtained by differentiation of equations (1) to (1*c*), D and I being expressed in minutes of arc and the intensity-components in CGS units, are determined as in equations (2).

$$\begin{aligned} \Delta X &= \cos D \Delta H - H \sin D \sin 1' \Delta D \\ \Delta Y &= \sin D \Delta H + H \cos D \sin 1' \Delta D \\ \Delta F &= \cos I \Delta H + \sin I \Delta Z \\ \Delta I &= (H\Delta Z - Z\Delta H)/(H^2 \sec^2 I \sin 1') \end{aligned} \tag{2}$$

The convention regarding algebraic sign, as above given, must be adhered to in using equations (1) and (2).

Magnetic methods to determine intensity.—The determination of the horizontal intensity by the magnetic method, developed by Gauss in 1832 and later modified by Lamont, requires that we measure the time of oscillation of a magnet suspended by a fine filament and free to oscillate in a horizontal plane about the filament as an axis and then measure the angle through which this magnet will deflect an auxiliary magnet when the latter is suspended at a known distance and direction from it. The relation between the time of oscillation, T, of the first magnet of magnetic moment M, its moment of inertia, K, and the horizontal intensity, H, is given by equations (3).

$$T = \pi\sqrt{K/MH}$$

or

$$HM = \pi^2 K/T^2 \tag{3}$$

In practice the time of oscillation is corrected for the rate of the chronometer or other timepiece with which it is observed, the effect of torsion of the supporting filament, the effect of induction of the Earth's field in increasing the magnetic moment of the magnet, and the effect of temperature on the moment of inertia and on the magnetic moment of the oscillating magnet. An instrument so designed as to make it feasible to make observations of this kind is called a magnetometer.

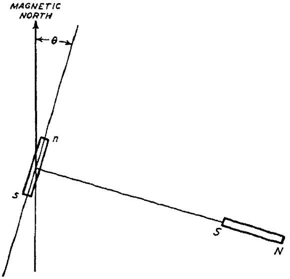


FIG. 2.—Position of magnets during the deflection-observation.

To measure the angle of deflection, the magnets are oriented with respect to each other as in Figure 2 (known as Lamont's first position). The deflecting magnet NS—the same as used for time of oscillation—is placed to the east of and at right-angles to ns, the auxiliary magnet. Designating the angle of deflection as θ, then

$$H/M = [(2/r^3)(1 + P/r^2 + Q/r^4 + \cdots)(1 - 2Mh/r^3)]/\sin\theta = C/\sin\theta \quad (4)$$

For convenience in computations the terms enclosed by brackets may be taken as a constant, C, for a given temperature. C is a function of the distance, r, between the magnets, of the dimensions of the two magnets—the distribution of their magnetism being expressed by distribution-coefficients, P, Q, . . —and of the induction-coefficient, h, of the deflecting magnet. The oscillating and auxiliary magnets are usually made of dimensions such as theoretically make either P or Q zero while succeeding terms in r^{-6}, r^{-8}, etc., are negligible. [For derivation of formulas and methods of reduction, reference may be made to the well-known "Directions for magnetic measurements" by Hazard, 122.]

The intensity of the Earth's magnetic field may be determined by means of a dip-circle using a method devised by Lloyd [38, 122], although values so obtained are not so reliable as those which may be obtained by a magnetometer. In this method a small weight is attached at one end of a dip-needle and the loaded-dip angle, I', is determined. The loaded dip-needle is then mounted at a fixed distance from an ordinary dip-needle so that the rotation-axes of the two needles are horizontal and in the same straight line with their magnetic axes at right-angles to each other at the time of observation, and the angle of deflection, θ, is observed. The value of F, the total field, may then be computed from equation (5).

$$F = C\sqrt{\cos I' \csc\theta \csc\theta'} \quad (5)$$

where $\theta' = (I - I')$ and C is a constant determined by observation at stations where I and F are known. The method is not much used at stations on land except in polar regions where the horizontal intensity is small. However, the method has been used extensively at sea.

Electromagnetic method to determine intensity.—The most accurate method of making an absolute measurement of horizontal intensity is by electromagnetic means. In this method, only practically realized recently although long since conceived, the magnetic field due to a known electric current passing through a coil of known dimensions is compared with the unknown horizontal component of the Earth's magnetic field at the center of the coil. A null-method may be used in which the horizontal component is just nullified or the coil-system may be used as a sine-galvanometer or tangent-galvanometer. In the sine-galvanometer, referring to Figure 2, the deflecting magnet is replaced by the coil and the value of H is obtained by the formula

$$H = G/\sin\theta \quad (6)$$

where G is computed from the dimensions of the coil and the absolute value of the current and θ is the deflection-angle [97].

II. EARLY HISTORY

Progress in constructing magnetic instruments was very sporadic before the work of Gauss early in the nineteenth century. As regards magnetic apparatus prior to that time, Crichton Mitchell [6], after a careful examination of all available historical documents, arrives at the following conclusions: "First, that the Chinese knew of the directive property of the magnet by the eleventh century and probably late in that century, namely, 1093 A.D., and second, that the application of this property to the compass in some primitive form had been made by the end of the eleventh century but this had been done, not by the Chinese, but by Arab or Persian navigators." The conclusions are based upon a treatise by Keou-Tsoung-Chy compiled between 1111 and 1117, which described the directive property of the compass-needle and stated that it always declined to the east of south as well as that the needle was suspended horizontally by a thread of cotton. However, Crichton Mitchell states that until the seventeenth century Chinese compasses were still in the form of a magnetized needle attached to a straw or a piece of wood.

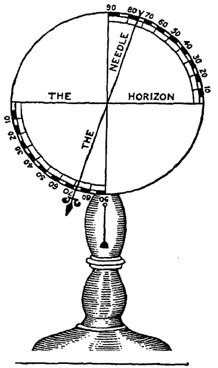


FIG. 3.—Sketch of first dip-circle constructed by Robert Norman; with it he measured magnetic dip for the first time at London in 1576.

From an examination of European documents Crichton Mitchell decides that the compass was in use in western Europe by 1187, the evidence for which appeared in two treatises by Alexander Neckam (1157–1217) entitled "De Utensilibus" and "De Rerum Naturis." In these treatises Neckam described the use of the magnetic needle to indicate the north and its specific use by seamen in steering a course when the Sun and stars were hidden, also stating that the needle was placed on a pivot, which can be generally understood as the second stage in the evolution of compasses. The third stage in compass-evolution was due to Petrus Peregrinus who, in a letter [6, reference 242], written in 1269, described the first form of azimuth-compass which he himself had devised and which has been illustrated in the magnetic literature by Bauer [24].

Crichton Mitchell [6] further traces the beginnings of the use of a compass in various countries in Europe until 1403 when it had become so regularly used that it was included in the inventory of a vessel made at that time. He also records that, from about the year 1450, Nüremburg sun-dials were correctly oriented in the true-meridian by the use of a magnetic compass and with a knowledge of the value of the magnetic declination.

It was not until several centuries later that an instrument was constructed for the measurement of the magnetic inclination or dip of the needle. Bauer [24, p. 32] records that G. Hartmann of Nüremburg observed in 1544 that after leveling an unmagnetized needle on its pivot there was a downward tendency of the north end immediately after magnetization. He, however, did not carry his experiment to its logical conclusion and did not measure the inclination. The first instrument for that purpose was invented by Robert Norman [35] in 1576 and his sketch of it is reproduced in Figure 3.

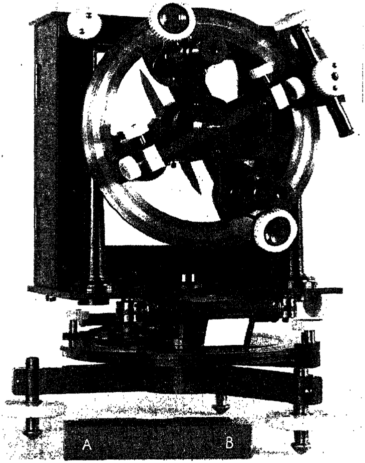


FIG. 4.—Dover dip-circle with loaded needle clamped outside (brass cover removed; load in end *B*) and deflected needle mounted on agates for determination of total intensity. (Note celluloid guards on tangent-motion screws to protect observer's fingers against cold in polar work.)

Norman's design was later developed to the Kew type of dip-circle, particularly through the splendid technique of three generations of the Dover family. A fine example of a modern Dover dip-circle is shown in Figure 4, which gives a view of the instrument as used in the determination of total intensity, *F*. The loaded dip-needle (load at end marked *B*) is mounted outside the housing (in the Figure the protecting cover of brass is removed so the loaded dip-needle may be seen) in the position for observing when the dip-needle mounted on the agate-bearings in the housing is perpendicular to the loaded needle. Note in particular the celluloid caps added to all metal parts which must be handled during observations—this is a modification adopted by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for use of instruments in polar regions to prevent freezing of observer's fingers in observational procedure.

The science of terrestrial magnetism had to wait another two centuries before the intensity of the Earth's magnetism was measured. Hazard [34, pp. 24–25] states that Frederick Mallet in 1769 was the first observer to measure the time of vibration of a compass-needle, thus obtaining relative values of horizontal intensity, and Jean Charles Borda in 1776 measured the time of oscillation of a dip-needle, thus obtaining relative values of total intensity. It was not until 1832 that Gauss, with the assistance of Weber, constructed an instrument for the measurement of absolute values of the Earth's horizontal intensity. Gauss thereby laid the foundation on which modern magnetic apparatus has been built.

III. TYPES OF INSTRUMENTS

It is convenient to divide magnetic instruments and equipment into three broad classes, namely: (1) Absolute instruments to determine values of the magnetic elements—(*a*) for use on land and (*b*) for use at sea; (2) variation-instruments and equipment to determine periodic and irregular variations—(*a*) for use at observatories and (*b*) for housing apparatus; and (3) for special purposes.

(1) Absolute instruments

(*a*) *Absolute instruments for use on land*

Since 1832 there has been steady improvement in the design of absolute instruments of several distinct types but all serve the same end. It is impossible, within the limits of the Chapter, to describe, or even list, all of these. Therefore, except for occasional references to some of the original designs, particular attention is given to more recent types with brief descriptions of some of the outstanding ones. Naturally, because of the pioneer work of Gauss and Weber in determination of the Earth's magnetic field intensity, the development of magnetometer-design went forward rapidly in Germany and France.

An interesting example of one of the early types of magnetometer, made a century ago by Gambey of Paris, is the Bache magnetometer (Fig.

5). This instrument was used in the magnetic survey of Pennsylvania—the first State magnetic survey in the United States—during 1840–45, and later by the United States Coast and Geodetic Survey by Professor Alexander Dallas Bache. Its oscillation-magnet was 20 inches long!

Great Britain early developed magnetometers for measuring declination and horizontal intensity. An excellent description of the Kew magnetometer is given by Chree [104]. A minor objection to this magnetometer may be cited, namely, during the measurement of the horizontal component of the Earth's field the time of oscillation of the suspended magnet is determined in one horizontal plane and the deflection-observation in another, slightly lower, horizontal plane, an objection of no importance where local disturbance is negligible as is the case for most magnetic observatories. The unusually portable and ingenious magnetometers constructed in France, described by Mascart [40], unfortunately contained magnetic materials in the housings, thereby giving erroneous observed values. Oglobinsky [145] developed a universal magnetometer

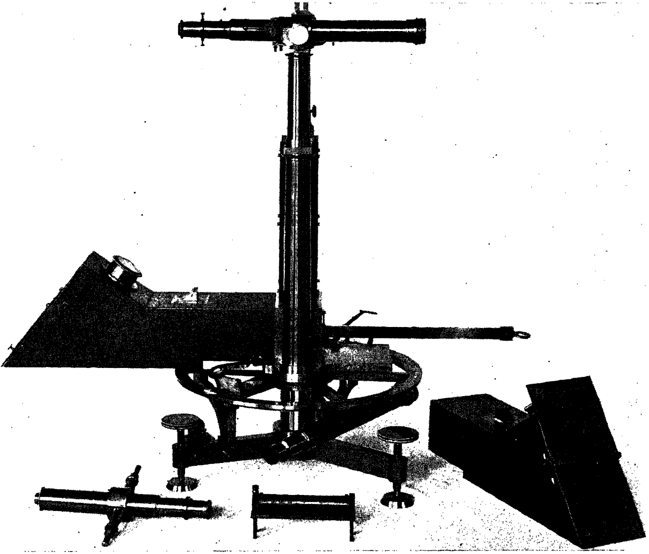


FIG. 5.—Bache magnetometer; one first used in magnetic survey of United States from 1840

for the measurement of declination, horizontal intensity, and vertical intensity, which has been used both at observatories and on magnetic surveys. Germany has produced many excellent magnetometers, the first being that by Wild [167], but it is complicated, quite large, and very massive. For the magnetic survey of India, a magnetometer, described by Fraser [118], was so well constructed that accurate observations of declination and horizontal intensity were obtained at either observatories or field-stations. In the United States, the Coast and Geodetic Survey has developed an excellent magnetometer, described by Hazard [122, pp. 62–66], which is similar to the India pattern. An instrument combining the best features of the India Survey magnetometer and of the design used by the United States Coast and Geodetic Survey, designed by and

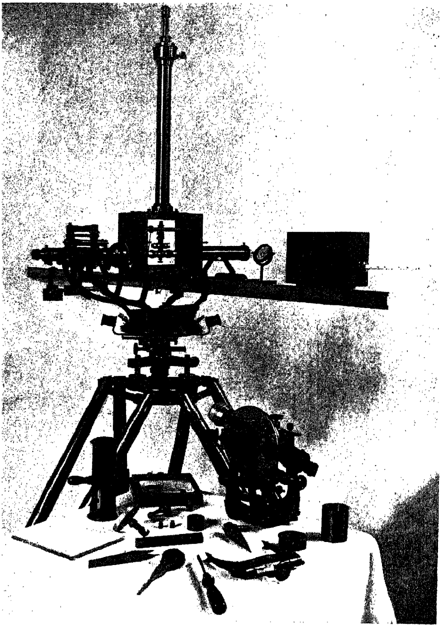


FIG. 6.—CIW type theodolite-magnetometer and appurtenances, combining best features of India Survey and United States Coast and Geodetic Survey.

constructed for the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, is shown in Figure 6.

Also in the United States, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington has designed and constructed a combined magnetometer and earth-inductor which combines the best features of the types developed by the India Survey and by the Coast and Geodetic Survey with other desirable improvements in design. This instrument (Fig. 7), described by Fleming [114], combines portability and simplicity without sacrificing the requisite accuracy. The complete instrument together with tripods weighs less than 50 pounds, distributed as follows: Instrument 16 pounds, tripods 15 pounds, and instrument- and tripod-cases 19 pounds.

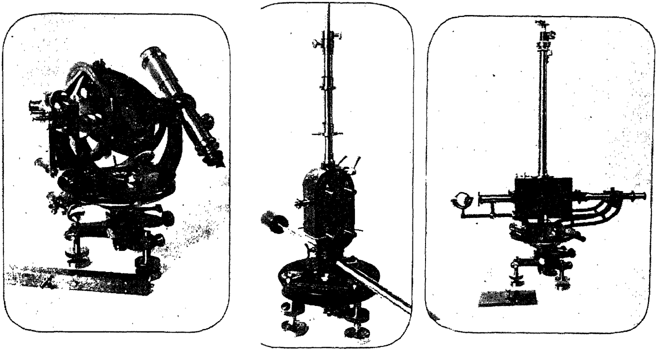


FIG. 7.—Combined magnetometer-inductor for determining magnetic declination, horizontal intensity, and inclination.

The combined magnetometer-inductor consists essentially of four main portions, namely: Base with horizontal circle; the assembly of theodolite, vertical circle, and earth-inductor; the magnetometer-attachment; and the galvanometer. Interested readers will find complete detailed description of the instrument in the above-mentioned references; only the more important features are given here. The cylindrical magnets are of such lengths that the second distribution-coefficient, Q, is theoretically eliminated. The magnets are enclosed in brass sheaths which carry the collimating optical-system, and the two magnet-systems are identical in weight and outside dimensions.

The entire suspension-system has no removable parts and the clamping-devices for the phosphor-bronze ribbon used for suspension are such that the ribbon may be quickly replaced and is easily centered. A graduated circle for determination of torsion is permanently attached to the stirrup which carries the magnet. The stirrup is readily raised and lowered by a rack and pinion in the head. The lines in the reticles and scale are sharply and accurately engraved.

The magnetometer-attachment is an assembled unit. The magnetometer-house is made entirely of old, well-seasoned mahogany. The magnetometer-telescope has an adjustable cap with convex spherical surface which closely engages a plush-lined concave spherical surface on the magnet-house when the telescope is horizontal, thus effectively serving to eliminate possible air-currents in the magnet-house. A simple and effective arrester is provided for quieting the motion of the suspended magnet. The rectangular deflection-bar is of brass, 5 by 15 mm in section. It is centered and held securely in place by two tapered pins; during travel it is carried in the instrument-case, thus being protected from damage.

The attachment for inductor and theodolite consists of a U-shaped frame supporting an inner ring in which are mounted the two agate-bearings for the inductor-coil. One bearing is adjustable to center the coil and the other has a longitudinal adjustment along its axis so that the coil may be maintained without lost motion in the bearings. The inner ring is supported by axles at each side, to which are attached the theodolite-telescope and the vertical circle. A compass which fits on the inner ring is provided for determination of the magnetic meridian. The galvanometer is of the Kelvin type with quartz-fiber suspension for the astatic magnet-system; it may be set up in a few minutes and withstands transportation perfectly.

Seventeen magnetometers of this type have been manufactured in the instrument-shop of the Department of Terrestrial Magnetism. The constants for these instruments are prepared from measured values of the deflection-distances, moments of inertia, and temperature- and induction-coefficients. The use of such constants permits observation of the values of the magnetic elements with these instruments with a precision of 0'.2 in declination, of $0.00015H$ to $0.00020H$ in horizontal intensity, and of 0'.2 in inclination. Bauer and Fleming [170] give the results of numerous intercomparisons of these 17 magnetometers with international magnetic standards and show that the mean differs from this standard by 0'.3 in declination, $0.0001H$ in horizontal intensity, and 0'.0 in inclination. In addition, they also report upon the result of 27 direct and 15 indirect comparisons of magnetic instruments obtained at a world-wide distribution of observatories and find that the mean differs from international magnetic standards by 0.1 in declination, $0.00003H$ in horizontal intensity, and 0'.1 in inclination.

When the corrections of individual magnetometers on international magnetic standards are examined, it is found that, though the average correction is small, the corrections of some of the magnetometers may be quite large, amounting to as much as 1′ in declination and inclination and $0.0008H$ to $0.0010H$ in horizontal intensity. These large differences are due to the use of materials which are not strictly non-magnetic, imperfections in manufacture, and, above all, the inherent errors in determination of the constants to be used in the reduction of the observations and in their control for changes with time—particularly moment of inertia of the oscillation-magnet and its support. Hence, it was inevitable that electromagnetic instruments should be developed whereby the Earth's intensity could be compared with the field produced at the center of a coil of known dimensions by measured electric currents.

In 1831, Faraday [see first volume of his "Experimental researches in electricity," 2d ed., pp. 42–75 (1849)], having previously discovered the laws for electromagnetic induction, perceived that the Earth should produce the same effect as a magnet and constructed the first instrument for measuring the Earth's magnetism. He rotated a copper plate and found that when it was rotated with its axis in the magnetic meridian and directed in the line of magnetic inclination, no current was produced in the galvanometer. Later, Weber further laid the basis for modern electromagnetic instruments when he mounted a coil with its axis horizontal and in the magnetic meridian. The circuit of the coil was completed through a ballistic galvanometer and the deflection measured when the coil was given a half revolution about a vertical axis. The first modern instrument, proposed and constructed by Tanakadate [159] in 1883, was an electromagnetic declinometer.

Watson [178] in 1901 constructed an electromagnetic magnetometer for the measurement of horizontal intensity. A Helmholtz-Gaugain coil wound on a gun-metal frame 30 cm in radius, together with the suspended magnet, was mounted on the base of a Kew magnetometer. Current-intensity was measured by the silver-deposition method. The coil-constants were known within an accuracy of five parts in 30,000 and horizontal intensity was measured with an accuracy of $0.00015H$. Watanabe [165] constructed in 1919 an electric magnetometer for use in the field to measure declination and horizontal intensity. The coils were wound on duralumin. Its constants were determined by comparison with a Helmholtz coil on a marble cylinder. This electric magnetometer yielded results of a comparable accuracy with regular magnetometers.

Schuster [154] in 1914 suggested a method of measurement of horizontal intensity using a Helmholtz-Gaugain coil. The instrument was constructed by F. E. Smith in 1920 and described [154] in 1922. The coils were wound on a hollow marble cylinder 30 cm in radius. The cylinder was carefully made and the coil-constants were believed known to one part in 100,000. The uncertainty in the current-measurement was about five parts in 100,000, and hence horizontal intensity may be measured with approximately the same accuracy.

The Department of Terrestrial Magnetism of the Carnegie Institution of Washington designed an electromagnetic instrument in 1913 (Fig. 8); it was not built until 1920 and is described by Barnett [97]. The coils arranged as in a Helmholtz-Gaugain galvanometer are wound on a hollow cylinder of Carrara marble. Each coil of the Helmholtz pair is wound in two parts so that it is possible to test the insulation. The coil is mounted on a horizontal circle 30 cm in diameter whose divisions have an accuracy of about two sec of arc. The magnetometer-box is from a solid block of pure copper. The magnet of chrome steel is a circular disk 20 mm in diameter and one mm thick. Both surfaces are polished; they are flat within a fraction of a wave-length of sodium light, are parallel within one sec

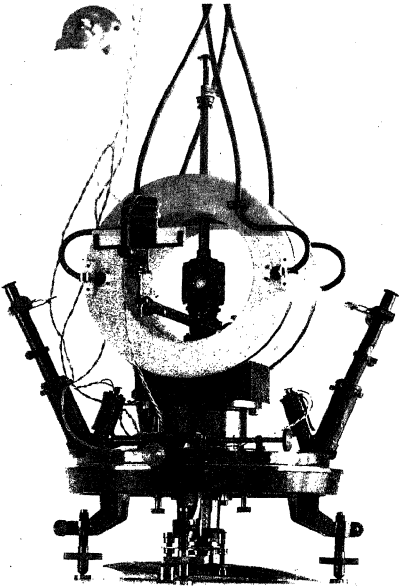


FIG. 8.—Sine-galvanometer for determining magnetic horizontal intensity.

of arc, and the angle between the surfaces and the magnetic axis of the disk is less than two minutes. The coil-constants were determined with an accuracy of three parts in 100,000. Suitable arrangements are made for the best possible determination of the current in the coil by mounting the standard cells, resistances, and source of current in a constant-temperature cabinet, thermostatically controlled (Fig. 9). Forbush and Johnson [175] state that the measurement of current is made within one part in 100,000 and with the probable error of a single determination of horizontal intensity of approximately five parts in 100,000. The observation of H can be made in two minutes by one observer. Through a cooperative arrangement between the Department of Terrestrial Magnetism of the Carnegie Institution of Washington and the United States Coast and Geodetic Survey, this sine-galvanometer, the constant-temperature cabinet, and accessories are now installed on special piers at the Survey's Magnetic Observatory at Cheltenham, Maryland. It is used regularly by the Observatory staff on all standardization- and control-observations involving horizontal intensity and serves as a national standard for this element.

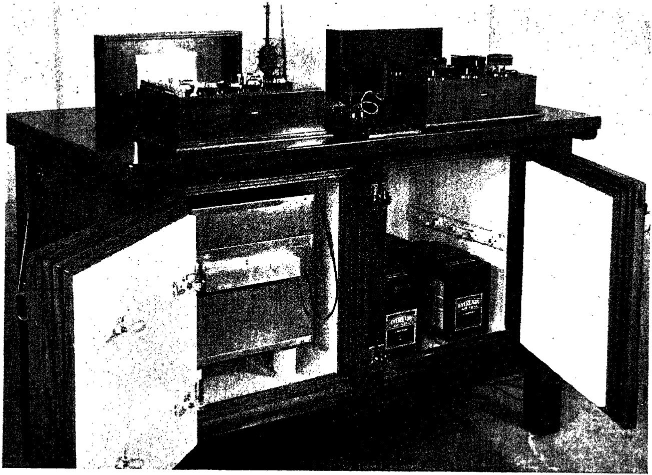


FIG. 9.—Cabinet for standard cells and electrical measuring appurtenances for sine-galvanometer.

To measure the vertical intensity of the Earth's magnetic field is more difficult than to measure the horizontal intensity. The value of the vertical intensity is regularly deduced from measured values of horizontal intensity and inclination. Since the inclination cannot be measured with great accuracy, the deduced values of vertical intensity are inaccurate and become less so as the angle of inclination increases toward the magnetic poles. This led la Cour [130] to consider an electromagnetic null-method for measuring the vertical intensity and to devise a novel vertical-intensity magnetometer. In this magnetometer a circular coil is turned about a horizontal axis with its plane horizontal to another similar position 180° from the original position. The flux-linkage so produced is balanced by the flux-linkage with the secondary winding of a mutual inductance when a known current-change is made in the primary winding. So far the measurements with this magnetometer have been relative since the coil-constants have been determined through comparison with magnetic measurements of vertical intensity at Rude Skov and Potsdam. However, by constructing a coil of known area, then real absolute determinations of vertical intensity may be made with this magnetometer.

Dye [107] has constructed a magnetometer for measuring absolute vertical intensity by electromagnetic methods. In this instrument the vertical intensity is balanced against the field produced in a vertical Helmholtz coil. The measurements consist in adjusting and measuring the current through the coil-system at that value which gives a field equal and opposite the Earth's vertical field. The indicator is a small, flat, light vibrating coil with its plane vertical and axis of vibration horizontal. An alternating current at the frequency of resonant vibration is sent through the coil and a large vibration results from the interaction between the alternating current and the Earth's vertical field. The vibration is reduced to zero when the field in the coil is exactly equal to the vertical field. The absolute value of the field at the center of the Helmholtz coil can be determined with an accuracy of two gammas (0.00002 CGS unit).

A new primary standard is nearing completion (1939) at the Department of Terrestrial Magnetism through cooperation of the United States Coast and Geodetic Survey, the National Bureau of Standards, and that Department. It is expected this instrument will give the absolute magnitude of the magnetic vector and of any of its components as well as the declination. The instrument consists of an accurately constructed Helmholtz coil, wound on a Pyrex-glass cylinder which has a low coefficient of expansion and whose dimensions are uniform to three parts in 1,000,000. The detector consists of a small rotating coil used with an alternating-current amplifier to detect the small voltage generated in the coil by the magnetic field. A null-method of measurement is used to determine any component, in a manner similar to that of Dye. The construction of the two coils is such that the constant of the instrument can be calculated to one part in 1,000,000. The absolute accuracy of the instrument is for the present determined essentially by the accuracy with which the absolute value of the amp is known, while the observational accuracy is one-fourth gamma (0.0000025 CGS unit) in any of the elements. For the first time this magnetometer allows the magnetic vector to be completely specified by a single instrument, while the time of observation for any element is about two minutes.

An electromagnetic magnetometer of the same type for use in the field is also under construction. The coils consist of duralumin ribbon wound on a coil-form of duralumin, and the coil-constant is obtained by comparison with the primary standard. The observational accuracy is about ± $\frac{1}{2}$ gamma (0.000005 CGS unit) with an absolute accuracy of about the same amount. The instrument will weigh approximately the same as the Carnegie Institution of Washington magnetometer-inductor but requires in addition a battery-supply which has been adapted for use in the field.

(*b*) *Absolute instruments for use at sea*

We now describe magnetic instruments specially designed for use at sea, where there is a special problem owing to the motion of the vessel. As mentioned previously, pivoted compasses with an azimuth-device were used as early as 1269 for the determination of declination at sea. The first expedition at sea for the observation of declination over a wide area was that of Halley in the *Paramour Pink* in 1698 (see Chapter I-V). The accuracy of declination-observations with the ordinary azimuth-device now used at sea is not better than 0°.5 in a non-magnetic vessel and in a magnetic vessel is of the order of 1° to 2°. This is due to the continual oscillatory motion of the compass-card in the horizontal plane and of the azimuth-device in a vertical plane, thus rendering possible only fleeting glimpses of the compass-card during the process of taking a bearing with the azimuth-device. In 1908, Peters [147] devised an instrument for accurately measuring declination at sea and called it the Carnegie Institution marine collimating-compass (Fig. 10). In this compass a standard United States Navy liquid compass has been used. The card was removed and replaced by four 10°-scales at the north, south, east, and west points. Four concave mirrors of speculum are mounted on the float so that the scales are in their focal planes. The bowl is provided with four windows, through which the scales may be seen when the bowl is properly oriented. The bowl is suspended in a gimbal-ring with four circular openings. The angle between the central division of the scale and any celestial body may be readily measured with a small sextant. The great advantage of the collimating-compass lies in the fact that the oscillation of the compass-card is visible and hence can be eliminated. The constants of the collimating-compass, consisting of scale-value, graduation-error, and effect of tilt due to change in magnetic latitude, are readily determined [147]. For a reasonably calm sea and with the celestial object within 10° of the horizon, magnetic declination is measured with an accuracy of 0°.1.

Horizontal intensity at sea may be measured by a simple deflection-apparatus, due to Bauer and Fleming [214], in which the deflecting magnet is mounted vertically above a compass and the angle of deflection is determined by comparison with an undeflected compass (Fig. 11). If the value of the deflection-angle is u, then the value of horizontal intensity, H, is given by the formula $H = (mC/\sin u)$, where m is the magnetic moment of the deflecting magnet and C is a function of the deflection-distance and its changes with temperature and of the induction- and

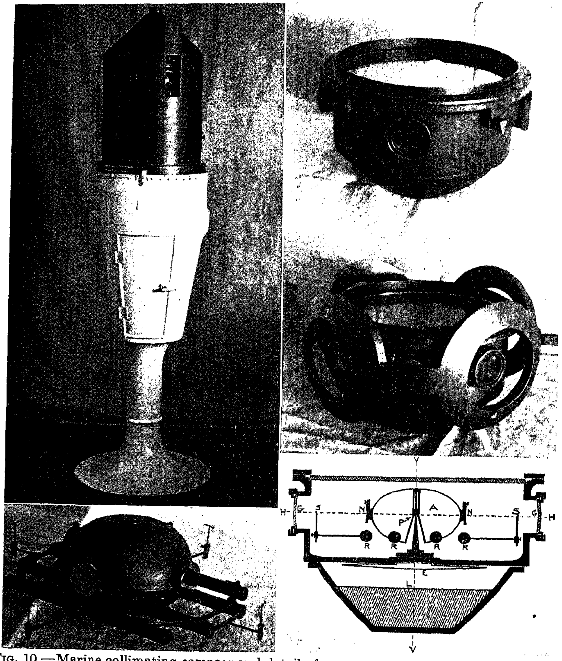


FIG. 10.—Marine collimating-compass and detail of magnet-system used on the *Carnegie*.

distribution-coefficients. The value of C is determined from observations on land. Liquid compasses have been used for these sea-deflectors, the liquid acting as a damping device. With this instrument, horizontal intensity may be measured with an accuracy of at least one part in 1,000.

Fox ["Annals of electricity," **3,** 288 (1839)] in 1835 adapted the dip-circle for measurements of inclination at sea. Later, Lloyd ["Proc. R. Irish Acad.," 1848] devised a method for using the dip-circle to determine total intensity at sea or on land (see section I). The most modern example of a dip-circle (Fig. 12) for use at sea is the design by Creak [134].

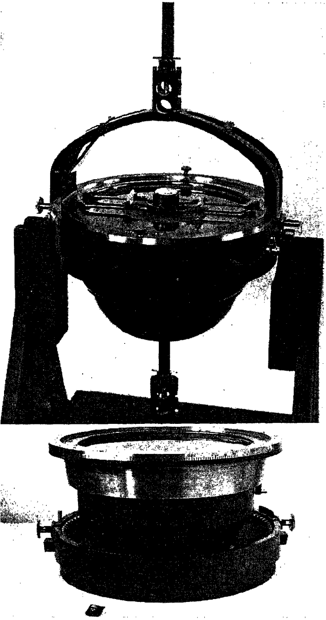


FIG. 11.—Deflector for determining magnetic horizontal intensity and declination at sea.

Dip-circles for use at sea, in common with those used on land, have the disadvantage that it is impossible to make perfect axles for the needles. On account of the inequalities in the needle-axles, the corrections to standard vary with magnetic latitude and it is therefore necessary to compare them with earth-inductors at different inclinations. This inherent disadvantage led Fleming [115] to adapt the land earth-inductor for use at sea. This inductor for use at sea, similar to the inductor for use on land, made by the Department of Terrestrial Magnetism, is ingeniously designed so that the coil may be rotated without disturbing the level (Fig. 13). In the earlier models, rotation was by hand, a chronometer being used to secure evenness in timing; in 1928, however, a constant-speed motor—remote from the inductor—was used on the *Carnegie* to rotate the coil of the inductor. In addition a specially designed gimbal-stand was manufactured to mount it (Fig. 14). In this gimbal the knife-edges are a hard alloy of platinum and iridium and they rest on slightly curved bearing pieces of agate. The outer ring is made in two parts which may be rotated relatively to one another, thus permitting of a 180°-reversal of the gimbal and tending to eliminate errors of level.

On land the method of observation with an earth-inductor is to determine, by means of a sensitive galvanometer, the position of the axis of rotation of the inductor in the magnetic meridian for which there is no current when the coil is rotated; this method is not feasible at sea. The method at sea is to measure the currents given by the rotated coil at two settings, one on either side of the line of inclination. The currents were originally measured on the *Carnegie* with a galvanometer having a moving coil supplied with balancing weights. However, in 1928, the galvanometer was replaced by a suitable radio amplifier and microammeter. With this equipment, inclination may be measured with an accuracy of 0°.1 at sea under moderate conditions.

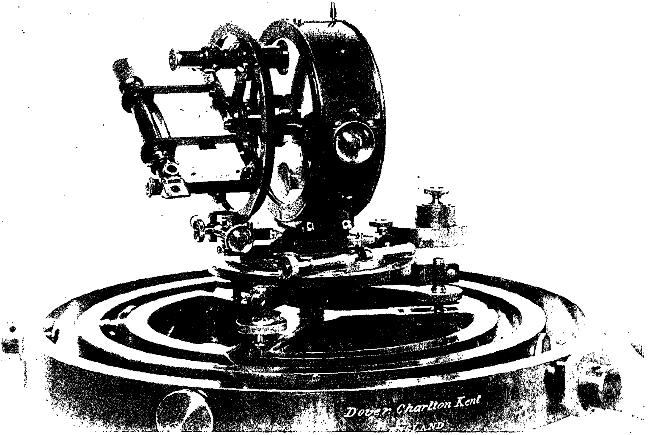


FIG. 12.—Modified Dover, Lloyd-Creak type dip-circle as mounted on gimbal-stand for use at sea

To record the output of an earth-inductor a method using an alternating-current amplifier and a cathode-ray oscillograph was developed by Johnson [127] which eliminates the effect of the motion of the ship on the recording instrument. The time at which the output goes through zero as the ship swings can be determined to within one-fiftieth second, and by recording the tilt of the earth-inductor with time, the inclination can be accurately determined. The same method can be applied to the measurement of declination.

(2) INSTRUMENTS AND EQUIPMENT TO DETERMINE PERIODIC AND IRREGULAR VARIATIONS

(a) *Instruments for use at observatories*

Early in the science of terrestrial magnetism a secular variation was found to exist but it was not until 1722 that George Graham, a London instrument-maker, definitely announced that a diurnal variation was present in declination, an account of which was published in the "Philosophical Transactions" in 1724. In 1834 Gauss established a special observatory for terrestrial magnetism at Göttingen, where frequent observations of the magnetic elements were obtained manually, thus giving continuity sufficient for the study of diurnal and other short-period phenomena. Continuous magnetic records by photographic means were first obtained at Kew in 1857 as announced by Balfour Stewart in the 1859 report of the British Association.

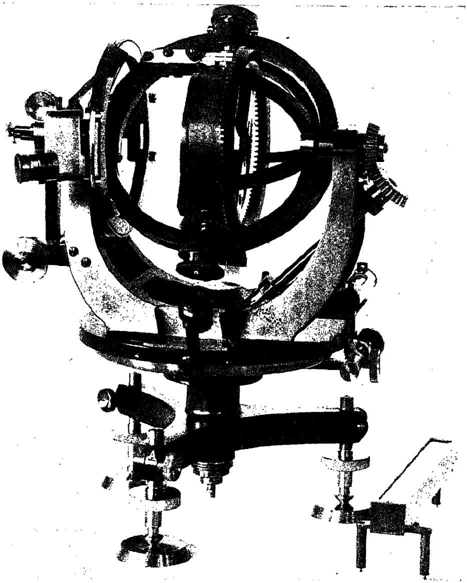


FIG. 13.—Marine earth-inductor for determining magnetic inclination.

Apparatus to record continuously the Earth's magnetism is called a magnetograph. It consists of a recorder and three units, or variometers, either declination, horizontal-intensity component, and vertical-intensity component, or east-intensity component, north-intensity component, and vertical-intensity component. Mascart [40] and Eschenhagen [109] describe modern magnetographs.

Declination variometer.—The modern declination variometer consists essentially of a small magnet attached to a light frame carrying a mirror, the whole being suspended by a fine quartz fiber free from torsion (see Fig. 15). This suspension-system is protected from air-currents by a suitable housing. Variations in the direction of the magnet are recorded photographically. Light from a suitable source is reflected, through an optical system of proper design, from the magnet-mirror and focused to a fine spot on a sheet of photographic paper (magnetogram) attached to a drum which is driven by clockwork at a constant speed. Whenever the magnet moves as a result of variations in the direction of the Earth's field, the light-spot traces an irregular curve (commonly called trace) on the magnetogram. The variometer is also provided with a stationary mirror mounted within the housing near the magnet-mirror. Light reflected from this fixed mirror is brought to focus also on the magnetogram and

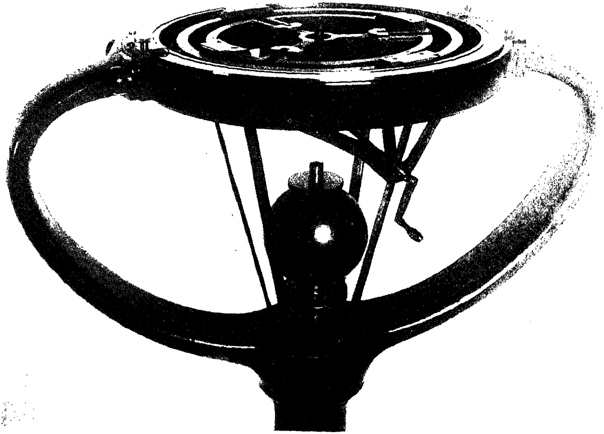


FIG. 14.—Reversible gimbal-stand for mounting instruments on board ship, as modified for mounting of marine earth-inductor.

records a straight line, or base-line. The variation in the perpendicular distance between this base-line and the trace is a measure of the variation in the direction of the suspended magnet, in this case a measure of the variation in magnetic declination.

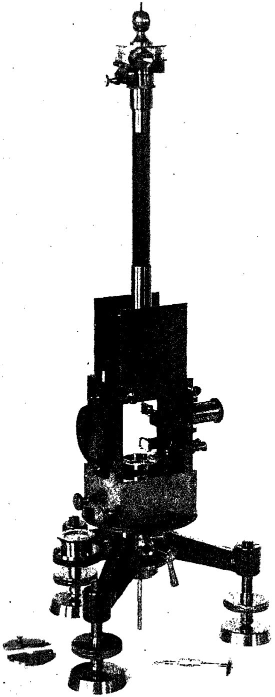


FIG. 15.—Variometer for determining variations in magnetic declination or in horizontal intensity.

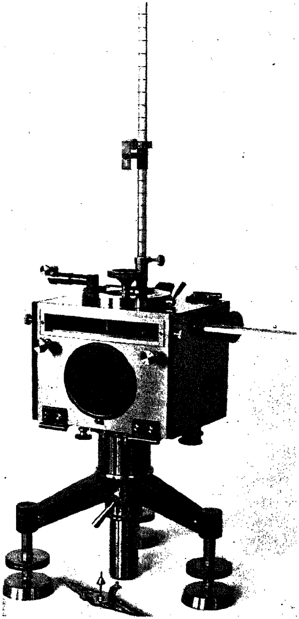


FIG. 16.—Variometer for determining variations in magnetic vertical intensity.

Horizontal-intensity variometer.—This instrument is similar to the declination variometer but in operation the suspended magnet is so oriented that its axis is perpendicular to the magnetic meridian. This is accomplished by twisting the fiber-suspension, the effect of torsion just balancing the magnetic couple acting on the magnet. If the horizontal intensity increases, the magnet will tend to turn back into the meridian, but if it decreases the torsion in the fiber will tend to make it turn in the opposite direction. Thus the position of the recording spot from this variometer relative to its base-line will be a measure of the horizontal intensity at that instant.

The horizontal-intensity variometer may be equipped also with a bifilar suspension instead of a unifilar suspension.

Vertical-intensity variometer (Lloyd balance).—The magnet of this variometer is so mounted that it will rotate about a horizontal axis as for a dip-needle. It is supported by pivots resting on agate-planes or by a knife-edge resting on agate-cylinders. The magnet-system is equipped with a mirror and optical system for photographic registration and is provided with balancing poises so that the magnetic axis may be adjusted to the horizontal. When so balanced the center of gravity is to one side of the axis of rotation. As the gravity-moment will be in equilibrium with the magnetic couple acting on the magnet, any change in the vertical intensity will result in a change of the inclination of the magnet and a corresponding change in the position of the light-spot from this variometer on the magnetogram. This variometer is also equipped with a fixed mirror for recording a base-line and with an optical thermograph for recording the changes in the temperature of the magnet. Figure 16 shows a modern type of vertical-intensity variometer.

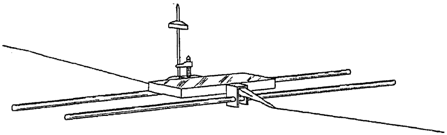


FIG. 17.—Sketch showing Watson type of quartz-fiber suspension for vertical-intensity variometer.

Because of generally unsatisfactory performance of magnetic balances mounted on knife-edges or pivots, Watson [166] designed a vertical-intensity variometer in which the magnet and its mirror are attached to the mid-point of a stretched horizontal quartz fiber (Fig. 17). This instrument is so delicate and requires such exceptional skill in mounting and adjusting it that it has not been extensively used.

Temperature-compensation of intensity-variometers.—Since the magnetic moment of a magnet varies with temperature, it is customary to provide some means of temperature-compensation on intensity-variometers. Three methods are in common use in effecting such temperature-compensation: Mechanical; magnetic; and optical.

The vertical-intensity variometer may be compensated by means of a threaded aluminum rod (carrying a bronze nut of suitable mass) attached to the magnet-system in such a way that as the temperature increases, causing the magnetic moment of the recording magnet to weaken and the magnetic couple to decrease, the gravity-restoring couple is reduced by an equal amount. By proper adjustment of the nut, these couples can be balanced quite effectively for large ranges of temperature [1408].

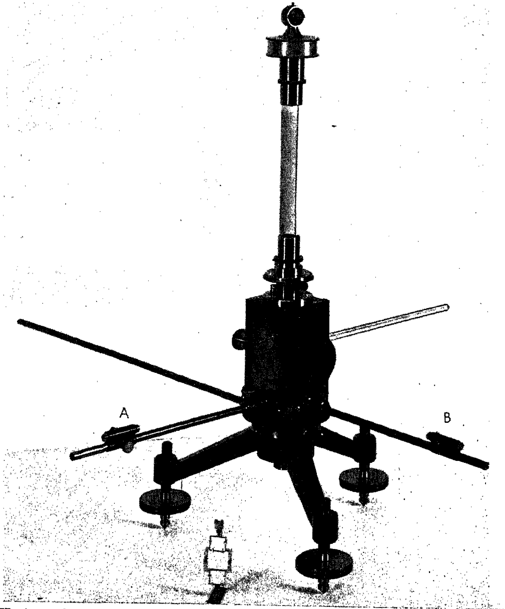


FIG. 18.—Horizontal-intensity variometer showing (*A*) temperature-compensation magnet and (*B*) sensitivity-control magnet.

The magnetic method of temperature-compensation is described by Schmidt [149-*A*] and by Hartnell [121-*A*]. In this method an auxiliary magnet, having the same temperature-coefficient as the recording magnet, is mounted directly below the center of the magnetic balance with its north-seeking end directed vertically upward (in north magnetic latitudes) and at such a distance as to reduce the vertical intensity at the center of the balance by approximately 50 per cent. The recording magnet is then rebalanced. Now as the temperature rises the magnetic moment of the recording magnet decreases (apparent decrease in vertical intensity) and the north-seeking end moves upward. At the same time the magnetic moment of the auxiliary magnet also decreases, causing an apparent increase in vertical intensity. These effects may be made to compensate each other by proper adjustment of the distance between the auxiliary magnet and the magnetic balance.

In optical compensation as used by la Cour [133], the light passes through a prism attached to a bimetallic strip in such a manner that the angular motion of the reflected ray due to movement of the magnet resulting from temperature-effects on the magnet is just compensated by its angular motion in the opposite direction due to temperature-effects on the bimetallic strip.

Magnetic and optical temperature-compensation may be applied also to horizontal-intensity variometers. Figure 18 shows such a variometer with the compensating magnet mounted at A on a horizontal bar of the variometer. The magnet at B is to control sensitivity.

Induction-variometer.—Induction-variometers were suggested years ago by Kashiwagi [1267-*A*] and Venske [1280-*A*]. Materials available then proved to be unsatisfactory. The invention of perminvar, an alloy of iron, cobalt, and nickel, with practically constant permeability and negligible hysteresis for low field-intensities, made it possible for McNish [140] to design and build at the Department of Terrestrial Magnetism a simple vertical-intensity variometer using some of this new material obtained through cooperation with the Bell Telephone Laboratories and the United States Coast and Geodetic Survey (Fig. 19). There are four vertical pieces of perminvar, designated as "field-pieces," each 5 by 5 by 52 mm mounted in pairs above one another on Pyrex-glass rods. Between the upper and lower field-pieces there is an air-gap of about 12 mm in which a non-homogeneous field exists and in which two smaller pieces of perminvar (the armature) are suspended by a fine fiber of quartz (Fig. 19). All of these pieces become magnets by induction from the vertical component of the Earth's magnetic field. The armature tends to rotate in the air-gap so that the flux through the field-pieces and the armature is a maximum. It is restrained from doing this by the torsion in the quartz fiber. The rotational motion of the armature is recorded photographically. The sensitivity of the instrument may be altered by using different quartz-fiber suspensions or by varying the distances between the field-pieces. Also, since the magnetic torque exerted on the armature varies with its vertical position between the upper and lower field-pieces, temperature-compensation is obtained by placing the armature in such a position that, as the armature rises and falls in the gap due to changes in temperature, the change in magnetic torque due to this cause may be arranged to be equal and opposite to the change due to the effect of change in temperature on the permeability of the alloy. The principle of this vertical-intensity variometer may be used to construct east-component and north-component variometers with the advantage that only one component of the field is measured regardless of the changes in direction of the magnetic field which always occur during magnetic disturbances.

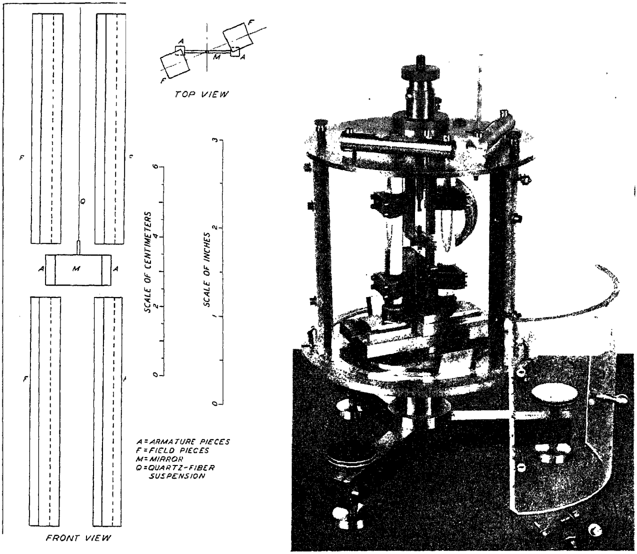


FIG. 19.—Schematic diagram and view, induction-variometer to determine variation in magnetic vertical intensity.

The Schmidt device for photographically recording large magnetic changes.—Ad. Schmidt has made provision for recording large changes in intensity and declination by an ingenious device [149-*A*]. An auxiliary mirror on the suspension-system of a variometer is so mounted that it faces almost vertically upward. The incident light, used for photographic recording, is directed to this mirror by a prism and the reflected ray passes back through this prism to the recorder. The angular motion of the spot (from this auxiliary mirror) due to rotation of the system is a function of the inclination of the mirror to the horizontal. Thus the adjustment of the magnification is continuous over a wide range.

The la Cour magnetograph.—A more recent type of magnetograph is that designed by la Cour for the International Polar Year of 1932–33. The vertical-intensity instrument [Godhavn balance, 131] is of unique design. The recording magnet is constructed of one piece of steel and weighs less than five grams. The knife-edges and the mirror are integral parts of the magnet. When in operation the knife-edges rest on agate-supports which are approximately cylindrical in section, but which are curved slightly upward forming surfaces which are somewhat saddle-shaped, like the inside of a toroid or ring. The system is so designed as to operate in a partially evacuated chamber (Fig. 20). It is optically compensated for temperature.

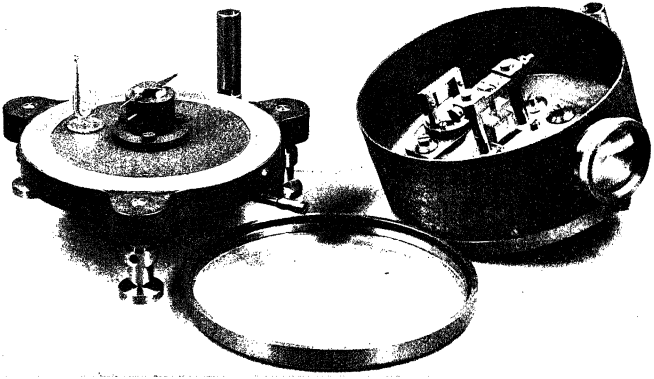


FIG. 20.—Vertical-intensity variometer designed for Second International Polar Year.

The la Cour H-variometer [133] is also optically compensated for temperature (Fig. 21-*A*). The magnet weighs only 25 mg and is about 8 mm in length. It is supported by a quartz fiber with enlarged ends. These ends rest in conical lugs, one attached to the torsion-head and the other to the frame of the magnet-mirror, and can be removed or replaced easily. This type of support makes it unnecessary to cement the fiber to the lugs and insures freedom from slipping (Fig. 21-*B*).

Since the changes in magnetic elements in the polar regions are very large, V. Laursen, utilizing the original suggestions of Ad. Schmidt [152-*A*],

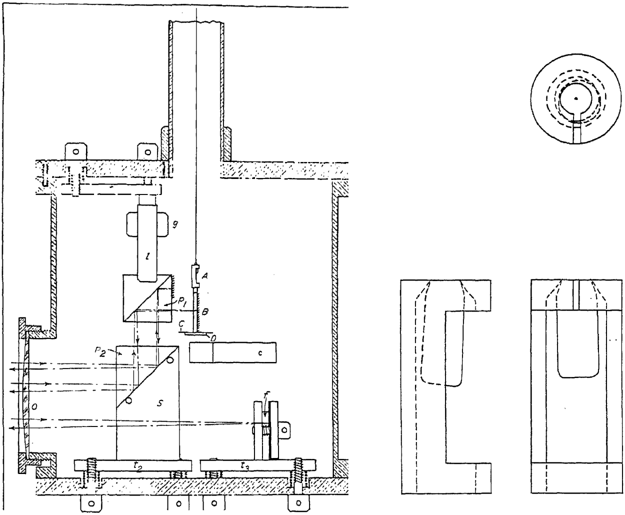


FIG. 21.—Schematic sketch of horizontal-intensity variometer designed for Second International Polar Year, and detail of quartz-fiber mounting.

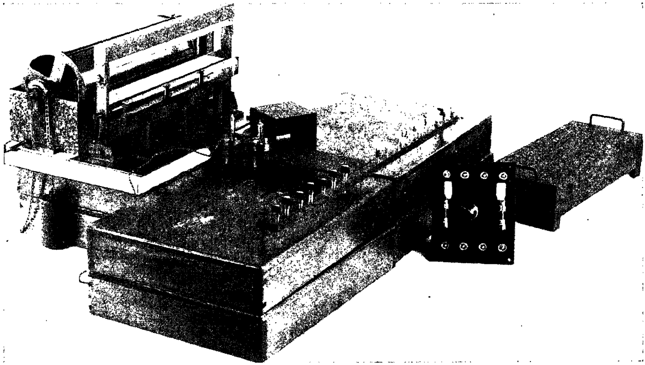


FIG. 22.—Recorder of magnetograph used during Second International Polar Year.

constructed a special recorder for large magnetic ranges (Fig. 22). A number of total-reflection prisms are placed between the lamp and the variometers. The distance between the prisms is so arranged that, before the spot from one prism goes beyond the edge of the recording paper due to the motion of the magnet, another spot from the adjacent prism comes on. Depending upon the scale-value and the number of prisms used, any probable range in the magnetic elements may be covered.

(b) *Equipment for housing apparatus*

The differences occasioned by changes of temperature on the constants of variation-instruments—for example, arising from changes in magnetic moments of the needles of the variometers—make it necessary to give particular attention to their housing, as at fixed observatories for recording over many years and at temporary stations established for special recording over shorter periods. The selection of a suitable site for a magnetic observatory to be continuously and uninterruptedly in operation for many years is difficult, because of the rapid spread and development of electric car-lines, electric power-stations, and other sources of artificial disturbance to the Earth's magnetic field. Uniformity in the distribution of magnetism within the area to be occupied for the several kinds of work at an observatory so as to avoid necessary reduction of the magnetic elements to a normal station and to avoid any cause for correction is a second important consideration. Other points to be considered include accessibility to the station, freedom from disturbing influences other than those arising from electrical sources such as local natural magnetic anomalies, facilities in the locality from which to obtain supplies and water for photographic work, and reasonable comfort of the observer. The chief requisites for the design of a suitable observatory, in which to install magnetographs or absolute instruments, are: (1) Elimination of all building materials which have any magnetic properties—this applies particularly for buildings to house variation-instruments; (2) arrangements for absolute and variation-instruments such that their mutual interaction will be inappreciable; (3) the building for measurement of absolute values to permit simultaneous determinations without danger of mutual interaction of magnets of several instruments, thus facilitating simultaneous comparisons of equipment and observations; (4) construction of the building for variation-observations to be such as to have as nearly a uniform temperature throughout the year as possible without employing expensive means for heating or cooling, with accommodations for at least two sets of variation-instruments.

Magneticians are not entirely in agreement that magnetic material should be rigorously excluded in a magnetic observatory not intended for absolute determinations but used only for the recording of variations of the elements. Indeed, several such variation-observatories have been constructed with brick walls and other more or less magnetic materials. However, the magnetic variations are functions of the absolute magnetic elements; therefore, if the absolute magnetic values are disturbed, as they certainly would be were even a slight amount of magnetic material present in the building, the question must arise whether the magnetic variations measured can be properly associated with the undisturbed absolute elements. Further, the magnetic behavior of some materials (for example, brick) cannot be regarded as constant owing to their susceptibility to changes in magnetism with seasonal changes. Therefore, it is the general practice now to have all the observatories at fixed magnetic stations constructed of non-magnetic materials.

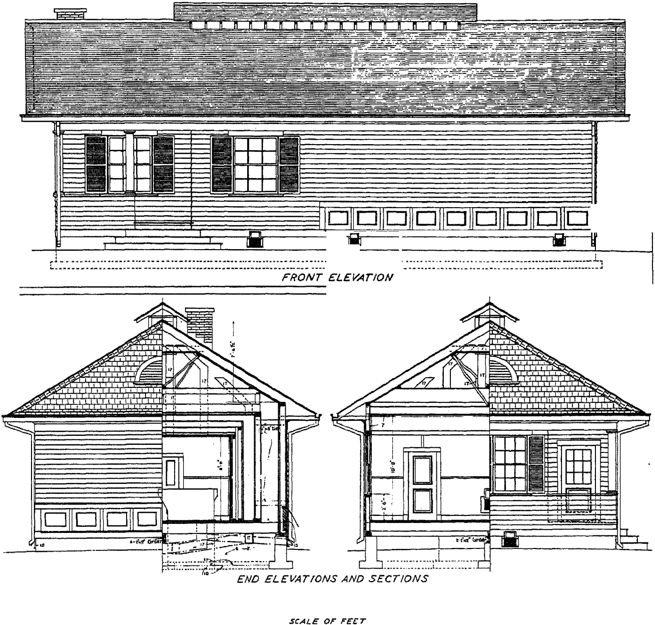


FIG. 23-*A*.—Design of magnetic-variation observatory and office, Watheroo and Huancayo magnetic observatories.

Originally, underground structures were used to house variation-instruments. However, it is practically impossible to eliminate in this construction difficulties arising from high humidity and the deleterious effects on instruments of moisture over long periods due to humidity and to ground-water seepage. The modern practice is to use above-ground structures, relying upon thermal insulation and appropriate arrangements

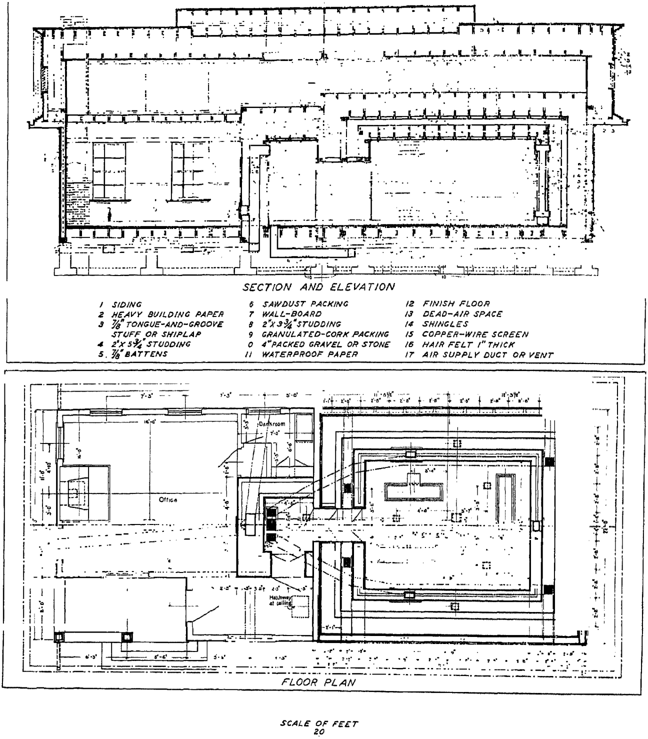


FIG. 23-B.—Design of magnetic-variation observatory and office, Watheroo and Huancayo magnetic observatories.

for ventilation to gain constancy of temperature. The success attending the use of such structures shows they satisfy temperature-conditions as well as an underground structure and have the advantage of greater economy in first cost and maintenance, convenience, and accessibility.

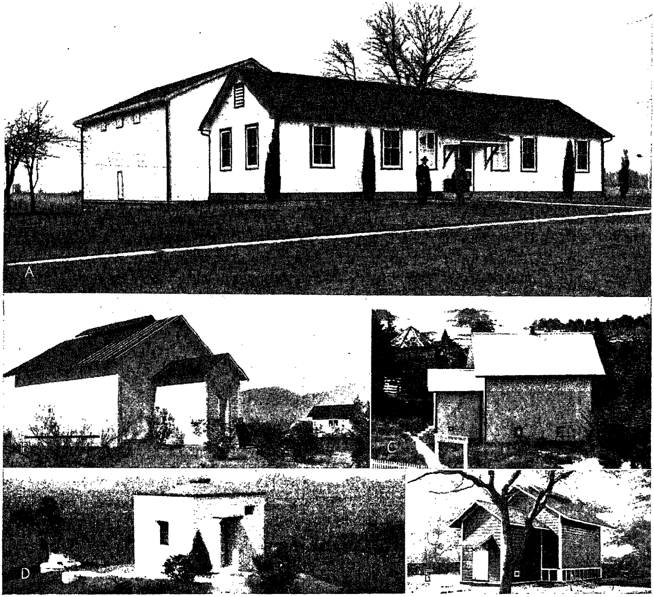


FIG. 24.—Views of the five United States Coast and Geodetic Survey magnetic observatories: (*A*) Cheltenham, Maryland; (*B*) Tucson, Arizona; (*C*) Sitka, Alaska; (*D*) San Juan, Puerto Rico; and (*E*) Honolulu, Hawaii.

The choice of an efficient, low-cost insulating packing for the walls, of which a considerable quantity will be needed, is important. Besides those specially manufactured insulating materials now on the market, which may be too expensive because of quantity, cheaper materials available locally may be used, for example, dry sawdust, straw, moss, or some such material. In any design, account should be taken of the heat-capacitance of the structure and its contents, as well as the properties of the insulating materials.

Figures 23 give the plan, elevations, and sections of the design used for the variation-observatories constructed by the Carnegie Institution of Washington at its magnetic observatories at Watheroo and Huancayo. This design has proved satisfactory. Views of the five magnetic observatories now operated by the United States Coast and Geodetic Survey are given in Figure 24. It has been found necessary in recent years to provide concrete aprons under various buildings of the United States Coast and Geodetic Survey Observatory at Cheltenham, Maryland, to guard against termites (wood-borers).

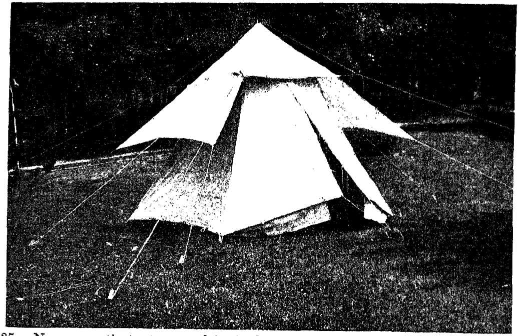


FIG. 25.—Non-magnetic tent as used in field to protect instruments (the fly is necessary for work in tropical countries) supported by a central wooden pole with spreader-arms at top. Height, nine feet; bottom, eight feet six inches by eight feet six inches; at spreader, three feet six inches by three feet six inches.

What has been said above with regard to construction of observatories on land applies equally well for vessels specially designed to determine accurate values of the magnetic elements at sea. The design and construction of the *Carnegie* was proved, through 20 years of cruising in all seas, to be entirely satisfactory. She was the first non-magnetic, auxiliary-powered vessel ever built. Details of construction, equipment, and materials of the *Carnegie* are being closely followed by the British Admiralty for its non-magnetic vessel *Research* now building. Complete descriptions and specifications of the *Carnegie* will be found in the published researches of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington [70].

Observing tent.—It is necessary, because of the high accuracy of observation required for determinations of the magnetic elements, that provision be made to protect instruments from Sun and wind in the field. For this purpose non-magnetic tents are generally used. One type of tent (Fig. 25), developed by Bauer, has been used satisfactorily in the field-work of the United States Coast and Geodetic Survey and of the Carnegie Institution of Washington. It is a pyramidal tent, supported by a central wooden pole, the two pieces of which when in use are joined by a non-magnetic brass sleeve. The use of spreader-arms, the ends of which fit into canvas pockets, gives sufficient room in such a tent (about nine feet square at the bottom) for the mounting of tripods and for observational procedure. For use in cold climates, a sod-cloth provides greater comfort within the tent, and for use in the tropics a fly aids greatly in reducing the range of temperature during observations.

(3) SPECIAL INSTRUMENTS AND EQUIPMENT

Compass-declinometer.—Frequently, organizations and institutions engaged primarily in geodetic, hydrographic, topographic, coastal, or other general mapping work, lack sufficient time to observe completely all three magnetic elements but do have time at numerous stations to determine values of magnetic declination. For this purpose pivoted compass-needles, as mounted on surveying transits, are frequently used. The index-errors of such instruments must be determined from time to time by comparisons at observatories where the declination is known accurately. A special declinometer has been developed by the United States Coast and Geodetic Survey (Fig. 26). When used with reasonable care it will furnish values accurate to about one minute of arc. The peep-sights serve to make readings on a mark of known azimuth and adjustable magnifiers attached to the compass-box permit of accurate readings of the ends of the needle. Thus from the circle-readings of the mark and the

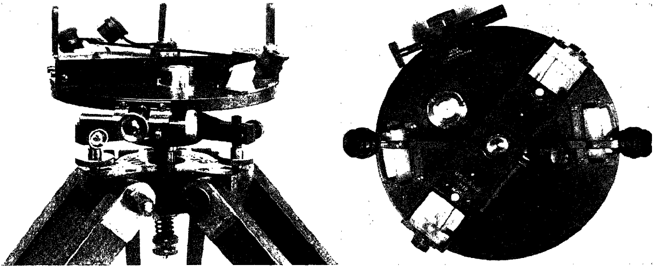


FIG. 26.—Compass-declinometer of United States Coast and Geodetic Survey.

needle and the known azimuth of the mark, the declination may be computed.

Transit-magnetometer.—This instrument is still being developed. It is simply an ordinary surveyor's transit made of tested, non-magnetic materials throughout. The needle is of special design, with a fine index-line on the upper surface of the north end, and its angular position may be observed to an accuracy of at least 0'.5 by a reading microscope designed for the purpose. It has the advantage over the compass-declinometer of being equipped with a reading microscope for observing the needle and a telescope for observing the mark accurately. In addition, it will be equipped with a special magnet-deflector of "Alnico" mounted in a fixed position on the objective end of the transit-telescope when the latter is accurately pointing to the zenith. By observing the deflection of the needle caused by the deflector it is expected that it will be possible to determine horizontal intensity to an accuracy comparable with that which can be obtained with an ordinary field-magnetometer and with greater ease and convenience in a much shorter time. The instrument will require that special precautions be taken in handling the deflector since its magnetic moment must be assumed to remain practically constant over intervals of a few months or until comparison observations can be made at a station where H is known. Several of these instruments are under construction for the United States Coast and Geodetic Survey.

Quartz horizontal magnetometer (QHM).—La Cour [132] in 1933 designed a quartz-fiber horizontal-force magnetometer to determine horizontal intensity by so-called "relative" methods (Fig. 27). A brass tube, so designed that it can be mounted conveniently upon the base of a magnetometer or theodolite, is equipped with suitable quartz-fiber suspension-system to which are attached a small mirror and magnet, the magnet having a magnetic moment of about two CGS units. The pear-shaped ends of the fiber are mounted in cone-shaped cups similar to those used in the la Cour variometers for H and D. The instrument is first standardized at a base-station where the horizontal intensity is known accurately. To observe horizontal intensity with this instrument the suspension is first released so that it will swing freely. The base is then rotated one or more complete turns to the right and then to the left, so that torsion in the amount of $+n \times 360°$ or $-n \times 360°$ is introduced into the fiber. From the observed deviations and the known instrumental constants the value of H may be computed readily. The weight of the instrument is but a few pounds so that it may be sent by mail between observatories. Recently, comparison observations were made at Cheltenham (Maryland) Magnetic Observatory with a *QHM*; the instrument was then sent to Sitka (Alaska) Magnetic Observatory for similar comparisons, and finally returned to Cheltenham for a second comparison. The results indicated that the comparisons with this particular instrument were accurate to two or three gammas. Examination of the results indicates that the uncertainty in the results would be somewhat less if the temperature-coefficient of the instrument were more accurately known for different temperature-ranges. Care must be exercised to see that control of the constants of such an instrument is maintained by frequent comparison with observed standards at a base-station. The instrument may be used also for study of local anomalies.

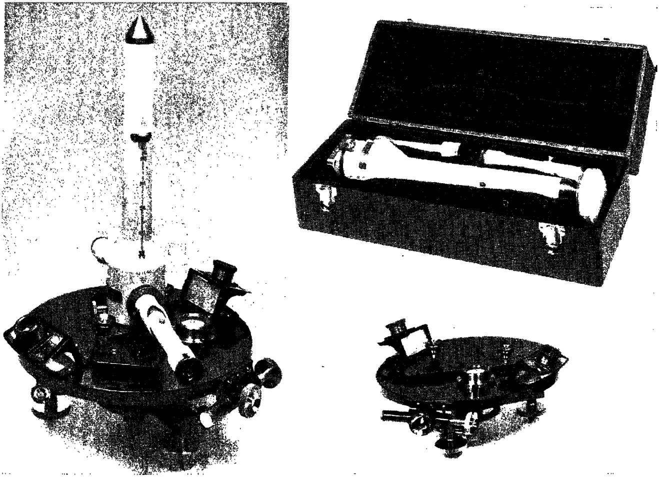


Fig. 27.—Quartz-fiber horizontal-intensity magnetometer (QHM) mounted on theodolite-base for relative measurements.

Compass-variometer.—For rapid surveys of high precision in horizontal intensity and investigations in magnetically disturbed regions such as those in buildings, around iron vessels, or in regions of local disturbance or at sea, the Department of Terrestrial Magnetism of the Carnegie Institution of Washington [99] has developed a compass-variometer. This instrument is an improvement of the deviation-compass of Captain W. Walker [1281] in 1853 and the double-compass of F. Bidlingmaier [100] in 1901. It consists essentially of two magnets of equal magnetic moment suspended independently one above the other and so mounted that the distance between them may be varied to maintain a fixed angle between their axes at any place (Fig. 28). The value of this angle is adopted according to the requirements of the particular problem. Determinations of horizontal intensity may be made with an accuracy of one gamma. As for all relative instruments, the constants of the compass-variometer must be controlled at a base-station from time to time.

Ship's compass, binnacle, and azimuth-circle.—Even though a ship may be of steel construction throughout, it is possible, by means of permanent magnets, soft-iron spheres, and soft-iron bars suitably mounted on or within the compass-binnacle (Fig. 29) to compensate, at the center of the ship's compass, for the magnetic field due to the permanent and sub-permanent magnetism of the ship. In practice the ship's compass is mounted in a non-magnetic binnacle permanently installed on the ship at such a position that it will be convenient for use in navigation. The compass is provided with an azimuth-circle (Fig. 29-*D*) for obtaining magnetic bearings of prominent objects ashore (known azimuth) or of the Sun, whose azimuth at any time may be computed. The difference

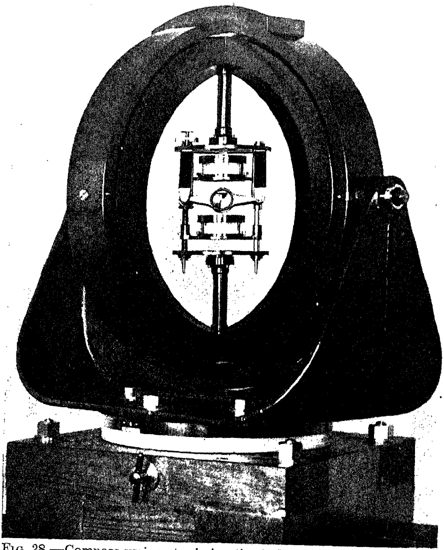


FIG. 28.—Compass-variometer in inertia gimbal-system for use at sea.

between these bearings is known as the compass-error and it would be equal to the magnetic declination at that time and place if the compass were perfectly compensated for the ship's magnetism. From time to time magnetic bearings of the Sun are taken on several headings, at a place where the magnetic declination is known accurately, and thus the deviation of the compass (angular difference from magnetic north as indicated by the compass) may be determined. If the deviation is known for all headings, declination at sea may be determined simply by taking a magnetic bearing on the Sun and making a correction for the deviation on that heading. [The theory of methods of compensation and correction of the compass was originally given by Poisson in 1824. Subsequent developments are found in the successive editions of the "British Admiralty Manual on the Deviations of the Compass"; see also 39 and 123-*A*.]

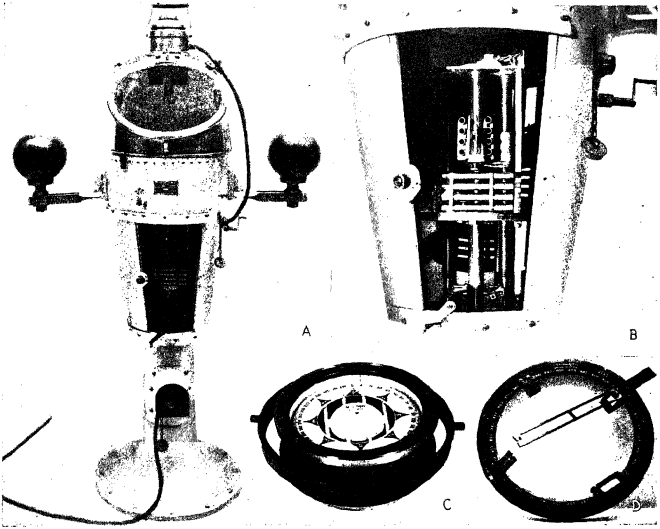


Fig. 29.—(*A*) Compensating binnacle; (*B*) detail of compass-compensation; (*C*) ship's compass and gimbal-ring; (*D*) azimuth-circle.

Miscellaneous instruments.—There are numerous other instruments designed for the determination of local magnetic anomalies and for geophysical prospecting. Knowledge of the distribution of vertical and horizontal intensity is most useful in this work. Adolf Schmidt [151] has designed such instruments with temperature-compensation. Vacquier [446] reports on a Schmidt balance made by the Askania Werke, which was used in a field-survey with a sensitivity of three gammas (0.00003 CGS unit) per scale-division. It is claimed that, with careful adjustments, the probable error of an observation in the field is only about one gamma. Complete descriptions of instruments for, and methods of, magnetic geophysical prospecting are given in Chapter III.

(4) INSTRUMENTAL CONSTANTS AND STANDARDIZATIONS

Even though magnetic instruments and accessories may be constructed with great precision and the utmost care taken in the selection and testing of materials to insure that they are non-magnetic, no two instruments can be constructed exactly alike. For this reason the results obtained with different instruments may differ more or less from each other or from the true values. It is important therefore that the constants of all instruments used in magnetic measurements be determined with great care when they are first placed in operation and at such times thereafter as may seem desirable and that they be standardized at intervals through comparisons with standard instruments. Instruments of different types require different technique in standardizations but in any case it is customary that comparisons with standard instruments should be simultaneous with, if possible, interchange of stations and observers in the middle of the series. Such interchange makes it possible also to determine station-differences and personal equation, both factors being of importance in precise work.

Declination.—Simultaneous observations are made with the instrument under comparison and a standard declinometer or magnetometer. The mean of all differences (adjusted for station-differences and personal equation) is taken as the index-correction of the instrument. For a magnetometer it is necessary to determine the equivalent in minutes of arc of one division of the scale in the telescope or in the magnet by observing the horizontal circle for different scale-readings.

Dip or inclination.—Dip-circles and earth-inductors are compared directly with a standard earth-inductor at an observatory, the mean difference of a series being taken as the index-correction for the earth-inductor or for a particular dip-needle. If a dip-needle is unbalanced, it is necessary to apply a correction for such lack of balance [122]. It is to be noted that because of the small diameter of the axle of a dip-needle and the resulting mechanical difficulty of making a perfectly round cross-section, the correction of inclination for any needle may vary for different values of inclination [115].

Horizontal intensity.—If the various constants used in the reduction of horizontal-intensity observations have been determined with the required accuracy at some previous time, it is sufficient simply to make simultaneous observations in the same manner as that followed for declination or dip, the standard instrument in this case being a magnetometer or sine-galvanometer. However, it is necessary to determine these constants when the instrument is first constructed and at regular intervals thereafter. These constants may be summarized as follows: Deflection-distances, r_1, r_2, r_3, etc; moment of inertia of the magnet-system, K; induction-coefficient of the oscillation-magnet, h; distribution-coefficients, P and Q; temperature-coefficient of the oscillation-magnet, q; torsion-factor of the suspension; and the linear coefficient of thermal expansion of the deflection-bar.

The deflection-distances are determined with special care, a comparator at a known temperature being used. In practice it is necessary to apply corrections for the change in these distances due to changes in temperature, and for this reason the linear coefficient of thermal expansion of the deflection-bar must be determined.

The moment of inertia of the oscillation-magnet and its suspension-system combined is determined by the kinetic method, that is, by determination of the period of the suspension-system, consisting of the oscillation-magnet, its stirrup, and accessories, first with a special inertia-bar mounted on the system and then without it. The inertia-bar must be carefully placed in the stirrup so that its center of gravity will be in the axis of oscillation of the system. If T is the time of oscillation without the bar (corrected for torsion-effect and temperature) and T_1 the time of oscillation with the bar (corrected as above), then the moment of inertia of the magnet-system is given by the relation

$$K = T^2K_1/(T_1^2 - T^2) \tag{7}$$

where K_1 is the computed moment of inertia of the inertia-bar reduced to the temperature for T_1 [122]. The inertia-bar usually consists of a tested non-magnetic cylinder of bronze, homogeneous throughout, and very accurately machined so that its dimensions may be measured to a high degree of accuracy. The determination of its mass to the desired degree of accuracy presents no serious difficulty. In the field and at an observatory the frequent handling of the oscillation-magnet, wear on its supporting stirrup, change in the mass due to oxidation, and possibly other factors, make it desirable to determine its moment of inertia every few years. The corrections required in many instruments on account of change in moment of inertia may become quite appreciable, sometimes being as high as $0.00030H$ per year.

The temperature-coefficient, *q*, that is, the effect on the magnetic moment of the oscillation-magnet for a change in temperature of 1°C, is of great importance. This coefficient may be determined as follows: The magnet is placed in a water-bath, the temperature of which may be varied over a wide range by simply heating and cooling the water. The container for the bath is so designed that it fits accurately on the deflection-bar of the magnetometer. It is necessary to hold the temperature practically constant for several minutes for each observation in order to insure that the temperature of the magnet is practically the same as that of the water in which the magnet is immersed. The temperature-coefficient may be checked by careful inspection of field-observations made at different temperatures. In general, the temperature-coefficient is not constant over wide ranges of temperature but for all ordinary ranges in temperature it may be taken as such.

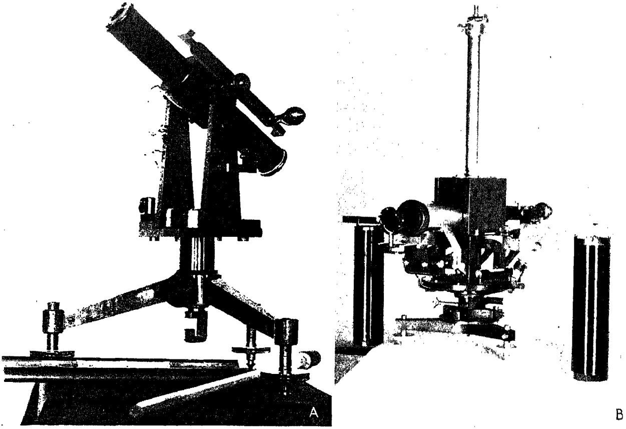


Fig. 30.—Apparatuses to determine induction-coefficient: (*A*) Weber's method, (*B*) electromagnetic method.

Distribution-coefficients, *P* and *Q*, may be determined readily by deflection-observations at three distances. They are then calculated by adjustment of the values of *H* as determined at the three distances in accordance with the equations involved [121-*B*, 122].

When a magnet is placed in a magnetic field such as the Earth's field, its magnetic moment is increased or decreased temporarily by magnetic induction in an amount which is proportional to that component of the field directed parallel to the magnetic axis of the magnet. The ratio of the change, ΔM, produced by unit-field to the original magnetic moment, M, of the magnet, is called the induction-coefficient, h, of the magnet. The product hM is known as the induction-factor, μ. For all practical purposes in ordinary observations with a magnetometer the induction-coefficient of a magnet is inversely proportional to its magnetic moment [143] and the induction-factor, $\mu = hM$, may be taken as a constant for that magnet.

There are several methods of measuring the induction-coefficient. In Weber's method (Fig. 30-*A*), the coil of a special apparatus is oriented with its long axis vertical so that it may be rotated in the plane of the magnetic prime-vertical while connected with a highly sensitive ballistic galvanometer. The coil is repeatedly rotated 180° in the vertical plane at intervals agreeing with the period of the galvanometer until a maximum deflection, a_0, is observed. The magnet under test is then mounted centrally within the coil and, upon rotating as before, a deflection, a, is observed. With the coil in a vertical position a small auxiliary magnet of known magnetic moment, m_1, is brought rapidly from some distance, placed within the coil in its vertical position and then quickly withdrawn, this being repeated until a maximum swing of a_1 is obtained. Then the induction-coefficient may be computed from the relation

$$h = m_1(a - a_0)/2MZa_1 \tag{8}$$

In Lamont's method, the magnet is used as a deflector with its axis vertical in the vertical plane perpendicular to the suspended magnet, with its center some distance above or below the horizontal plane through the suspended magnet. Observations are made (1) with the north end up and magnet up and with the north end down and magnet down and (2) with the magnet reversed in its vertical position. The difference in the magnetic moment in the two positions, (1) and (2), is proportional to the vertical intensity of the Earth's field. Thus, if constant conditions are maintained, h may be computed from the change in the deflection-angle, which is u_1 for (1) and u_2 for (2), by equation (9).

$$\begin{aligned} h &= \tan[(u_2 - u_1)/2] \cot[(u_2 + u_1)/2]/Z \\ &= \tan[(u_2 - u_1)/2]/H \tan I \tan[(u_2 + u_1)/2] \end{aligned} \tag{9}$$

It has been shown theoretically [121-*B*] that for any horizontal distance between the magnets, as used in Lamont's method, the deflection-angle is a maximum when the vertical distance is just one-half the horizontal distance between the centers of the magnets; this relation has been verified experimentally [138].

The induction-coefficient may be determined by an electromagnetic method, in which an artificially created magnetic field is used [143].

Instead of reversal of the deflector as is done in Lamont's method, the deflector is kept in one position and the field is reversed. The artificial field is supplied by two solenoids suspended from the deflection-bar of the magnetometer (Fig. 30-B) and the deflector is suspended centrally within one of the solenoids. The two solenoids are identical and are spaced equidistant from the suspended magnet in the magnet-house so that the resultant horizontal component of the magnetic field created by them (when energized) in the region of the suspended magnet is practically zero. In practice the coils are connected in series so that the same current flows in both and so that both fields are directed up or down at the same time. Several dry-cells provide the power and a milliammeter indicates the current. The chief advantages of this method are as follows: (*a*) The value of Δu, that is, the increase in deflection-angle caused by the applied field, may be observed directly on the scale in the magnetometer-telescope without the necessity of disturbing the deflector, the magnetometer, or any of the accessories attached to the magnetometer; (*b*) individual values of Δu may be determined in a few seconds while in Lamont's method a determination of Δu requires 20 to 30 minutes, depending upon the skill of the operator, magnetic conditions, accuracy of construction of the deflector holder, etc.; (*c*) practical elimination of uncertain errors caused by natural changes in horizontal intensity and declination during an observation; and (*d*) the method makes it possible to determine the induction-coefficient of a magnet whose coercive force is quite high. (For example, it would be almost impossible to determine the induction-coefficient of a magnet of "Alnico" by Lamont's method.)

Non-magnetic material for instruments.—A most important factor in the construction of magnetic instruments—one unfortunately frequently overlooked in the past and of first importance to precision in standards—is that all materials used must be non-magnetic. Instrument-makers interested in producing the finest kind of instrument sometimes thoughtlessly fail to observe this requirement, thinking all brasses and bronzes are non-magnetic. Most rigid control should be exercised as many instruments of fine construction have been found defective in this regard, sometimes to such an extent that, for a slight change in the height of a suspended magnet in its housing, observations of declination have shown differences of one to two minutes and at times considerably more, because of the presence of magnetic materials. Such defects vitiate any values obtained with such equipment. Therefore, it is desirable to have testing apparatus of great sensitivity to detect any traces of magnetic impurities in castings for parts of all instruments used for magnetic observations.

There has been developed recently a method [158] of making completely non-magnetic castings. An astatic magnetometer suitable for accurate testing of magnetic character of all metals used in magnetic instruments is shown in Figure 31. The magnets of the astatic system are 2.5 mm in diameter and eight mm in length supported by a quartz fiber six to eight microns in diameter. The magnet-system is made completely astatic by demagnetizing the stronger of the two magnets in the manner described by Johnson and Steiner [128]. The astatic magnetometer is quite rugged and may be used to measure the magnetic susceptibility of materials. The sensitivity may be adjusted from 2×10^{-8} to 1×10^{-5} electromagnetic CGS unit per scale-division.

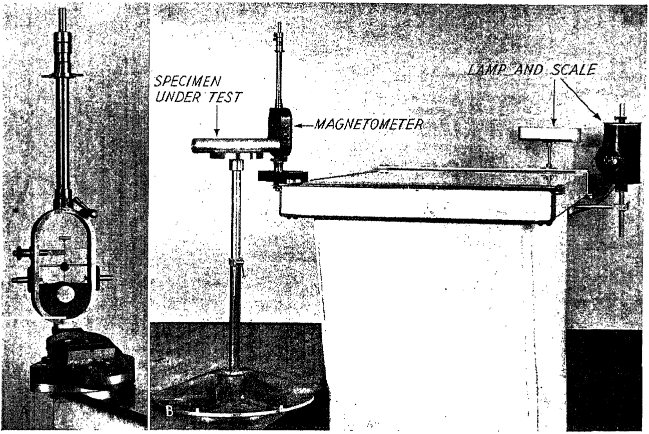


Fig. 31.—CIW astatic magnetometer for testing magnetic character of materials.

IV. PRACTICE AT MAGNETIC OBSERVATORIES

The primary function of a magnetic observatory is to obtain continuous photographic records of the magnetic elements, for example, of D, H, and Z or of X, Y, and Z, from which variations in the Earth's field may be completely determined. It is necessary to correlate these records with absolute observations made at regular intervals, so that absolute values (or average values) of any element or component of that element may be scaled, with sufficient precision, for any particular instant (or interval) directly from the magnetogram. That the results may be made available in convenient form for practical use, definite programs of observation, test, standardization, and reduction must be followed.

For convenience it is customary to operate the magnetograph so that a magnetogram represents a 24-hour run, time being marked on the magnetogram automatically every hour by a suitable time-marking clock whose rate and correction are determined accurately by comparison with radio time-signals at regular intervals.

Absolute observations of D, H, I, and/or Z are made once or twice per week, to control the performance of the magnetograph. These are made in an absolute observatory situated near the building which houses the magnetograph (variation-observatory) but at such a distance that there will be no appreciable interaction between the magnets of the different instruments. The times of beginning and ending of a set of absolute observations for a particular element are marked photographically on the magnetogram so that, later in the process of reduction, the appropriate segment of the record may be measured and compared with the observed absolute value of that element.

That absolute values of the declination or intensity may be estimated at a given time or for a given interval from the magnetogram, it is essential that the following be known: (*a*) The distance between the point (or segment) of the curve and the corresponding point (or segment) on the base-line; (*b*) the base-line value, that is, the absolute value of the particular magnetic element when the curve and the base-line for that element coincide; (*c*) the scale-value of the variometer, that is, the value of one mm of the ordinate expressed in gammas for intensity or in minutes of arc for declination; and (*d*) the temperature-coefficient of the variometer, that is, the change in the ordinate on the magnetogram due to a change in temperature of 1°C. of the variometer.

In the case of the D-variometer, the scale-value is expressed in minutes of arc. It varies inversely as the distance between the lens of the variometer and the face of the recording drum at the point of registration (optical lever). For convenience in scaling of ordinates, this distance is made such that the scale-value will be approximately one minute of arc per millimeter of ordinate on the magnetogram. To determine the scale-value in D it is necessary to make corrections for the thickness of the lens of the variometer and of the cylindrical lens of the recorder, for the torsion-factor of the quartz-fiber suspension, and for the fields of other magnets of the magnetograph.

Since the H-variometer is an intensity-instrument its scale-value depends not only upon the length of the optical lever but also upon several other factors such as the size, length, and rigidity-modulus of the suspension-fiber (in unifilar instruments), the magnetic moment of the variometer-magnet, and upon the field of any auxiliary magnet which may be attached to the variometer for scale-value control [117, 121, 125-*A*]. Similarly, the scale-value for Z depends upon the length of the optical lever, the magnetic moment of the recording magnet and its orientation with respect to the magnetic meridian, on the value of the horizontal intensity, and on the vertical distance between the center of gravity of the system and the horizontal line of support (knife-edge or line joining the pivot-points). The scale-value of an intensity-variometer is determined by changing the field at the center of the variometer-magnet by a known amount and noting the deflection of the recording spot on the magnetogram. The artificial field is supplied either by a known current in a Helmholtz-Gaugain coil which is mounted permanently in place around the variometer or by use of a large auxiliary deflector-magnet (known magnetic moment of 7,000 to 14,000 CGS units) placed at a definite distance (2 to 4 meters) and direction from the variometer and with its axis in proper orientation [135].

From the values of the declination, D, as determined in the absolute observatory, of the scale-value ϵ_D, and the distance, d, between the base-line and the corresponding point on the D-trace of the magnetogram, the absolute value of the base-line, B_D, may be computed from equation (10).

$$B_D = D - d\epsilon_D \tag{10}$$

Values for base-lines of H and Z may be determined similarly. Under satisfactory operating conditions the base-line values will remain constant over a sufficient length of time so that absolute values for any instant or average values for any interval of time may be obtained directly from the magnetograms.

The temperature-coefficient, q, of a variometer should be determined carefully from time to time [139] and if it is shown to be appreciable it must be taken into consideration in the computation of the base-line values or in scaling of absolute values from the magnetogram. For example, if B_h is the horizontal-intensity base-line value at standard temperature, ϵ_H the scale-value for H, h the ordinate in millimeters, t the temperature of the variometer at the time of registration, t_0 any standard temperature to which all of the scalings are referred, and q_H the temperature-coefficient of the H-variometer, then the value of the horizontal intensity, H, at a particular instant or interval corresponding to the ordinate, h, is given by

$$H = B_h + h\epsilon_H + q_H(t - t_0) \tag{11}$$

For convenience in publication and subsequent use, the average values of the ordinates are scaled for each hour of the day. The scalings are made with a special reading glass (Fig. 32-A) placed directly on the magnetogram and so adjusted that the vertical lines coincide with the hour-marks on the magnetogram and so that a horizontal line on the scale is set for the average ordinate (between adjacent vertical lines) of that segment of the curve to be measured. The ordinate is then read on the base-line to the nearest one-tenth mm and its value is computed from an

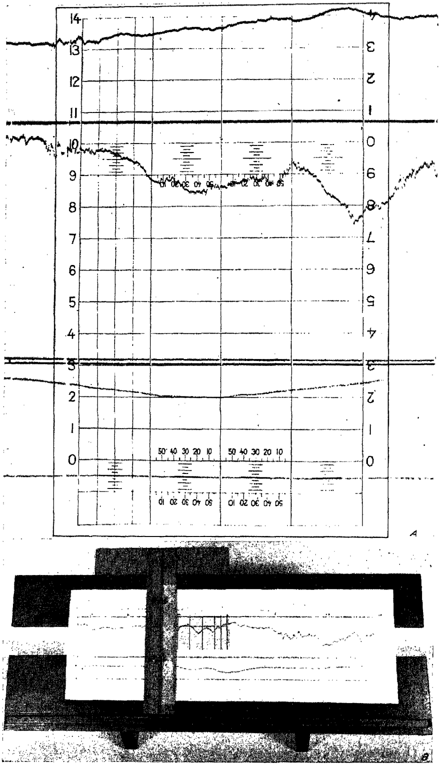


FIG. 32.—(*A*) Etched reading glass used for scaling ordinates and (*B*) special reading board for direct scaling of ordinates.

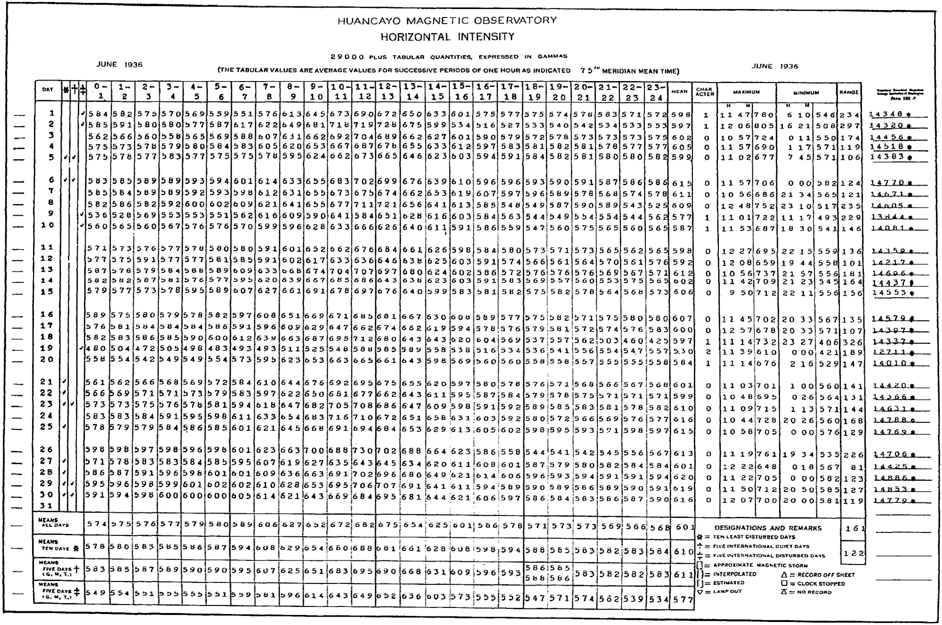
equation similar to equation (10) or (11). It is obvious that an enormous amount of labor is involved in the scaling, reduction, and tabulation of these hourly values systematically for various elements over long periods of time.

To minimize the number of steps involved in the process of reduction, a scheme of direct scaling of ordinates has been devised [1269-*A*]. It involves the use of special aluminum scales so divided that one division on the *H*- and *Z*-scales is equal to five or ten gammas on the magnetogram and one division on the *D*-scale is equal to one minute on the magnetogram. In practice the scale is clamped on a T-square and is mounted with the magnetogram and reading glass on a special reading board as shown in Figure 32-*B*. The magnetogram is adjusted so that the base-line of the element to be measured comes under its value on the scale. The record of the element to be scaled will then fall under its absolute value on the scale as the T-square is moved along the straight-edge of the reading board. The reading glass is used for estimation of average ordinates and its index will indicate the average hourly absolute value on the aluminum scale.

The values of the magnetic elements are tabulated and published for convenient use as shown in Figure 33.

An isolated magnetic observation of any magnetic element (no matter how precisely it may be made) without detailed information as to location, elevation above the surface of the ground (in a disturbed area), date, and local time at which the observation is made would be of little value in the preparation of magnetic tables and charts, in the computation of secular changes by reference to previous observations made at or near the same site, or in general scientific studies in terrestrial magnetism. Secular-change tables are based upon continuous or periodic observations made at fixed magnetic observatories or at selected magnetic stations which experience has shown meet most of the essential requirements for such a station. Where such stations are not regular magnetic observatories, the observations of declination are corrected for diurnal variation from data based on results obtained from the nearest magnetic observatory, from data obtained from continuous eye-readings at the station for several days, or from magnetograms produced by a temporary or portable magnetic observatory established in the region for the purpose of providing local control. The diurnal variations of *H* and *Z* are so irregular with latitude that it is difficult to correct them by using data from a remote observatory. The continuous eye-reading observations or the results from a temporary observatory should furnish satisfactory mean values of the elements for use in computing secular change however.

The temporary or portable magnetic observatory is, probably, the most satisfactory solution of the problem of local control and should, in the end, furnish the most reliable data. An observatory of this kind should



HUANCAYO MAGNETIC OBSERVATORY
HORIZONTAL INTENSITY

JUNE 1936

29000 PLUS TABULAR QUANTITIES, EXPRESSED IN GAMMAS
(THE TABULAR VALUES ARE AVERAGE VALUES FOR SUCCESSIVE PERIODS OF ONE HOUR AS INDICATED 75TH MERIDIAN MEAN TIME)

JUNE 1936

DAY	✱	†	‡	0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	10-11	11-12	12-13	13-14	14-15	15-16	16-17	17-18	18-19	19-20	20-21	21-22	22-23	23-24	MEAN	CHARACTER	MAXIMUM			MINIMUM			RANGE	[illegible] Form 180 A
																														H	M		H	M			
1			✓	584	582	575	570	569	559	551	576	613	645	673	690	672	650	633	601	575	577	575	574	578	583	571	572	598	1	11	47	780	6	10	546	234	14348 ✱
2			✓	585	591	580	580	577	587	617	622	649	681	718	719	728	675	599	534	516	527	533	540	542	534	533	553	597	1	12	06	805	16	21	508	297	14320 ✱
3				562	566	560	558	565	569	588	607	631	662	692	704	689	662	627	601	590	579	572	578	573	573	573	575	602	0	10	57	724	0	11	550	174	14456 ✱
4				575	573	578	579	580	584	583	605	620	653	667	687	676	655	633	612	597	583	581	582	581	578	577	577	605	0	11	57	690	1	17	571	119	14518 ✱
5	✓	✓		575	578	577	583	577	575	575	578	595	624	662	673	665	646	623	603	594	591	584	582	581	580	580	582	599	0	11	02	677	7	45	571	106	14383 ✱
6	✓	✓		583	585	589	589	593	594	601	614	633	655	683	702	699	676	639	610	596	596	593	590	591	587	586	586	615	0	11	57	706	0	00	582	124	14770 ✱
7				585	584	589	589	592	593	598	612	631	655	673	675	674	662	653	619	607	597	596	589	578	568	574	578	611	0	10	56	686	21	34	565	121	14671 ✱
8				582	586	582	592	600	602	609	621	641	655	677	711	721	656	641	613	585	548	549	587	590	589	543	525	609	0	12	48	752	23	10	517	235	14605 ✱
9			✓	536	528	569	553	553	551	562	616	609	590	641	584	651	628	616	603	584	563	544	549	554	554	544	562	577	1	11	01	722	11	17	493	229	13844 ✱
10			✓	560	565	560	567	576	576	570	599	596	628	633	666	626	640	611	591	586	559	547	560	575	565	560	565	587	1	11	53	687	18	30	541	146	14081 ✱
11				571	573	576	577	578	580	580	591	601	652	662	676	684	661	626	598	584	580	573	571	573	565	562	565	598	0	12	27	695	22	15	559	136	14359 ✱
12				577	575	591	577	577	581	585	591	602	617	633	636	646	638	625	603	591	574	566	561	564	570	561	576	592	0	12	08	659	19	44	558	101	14217 ✱
13				587	578	579	584	588	589	609	633	668	674	704	707	697	680	624	602	586	572	576	576	576	569	567	571	612	0	10	56	737	21	57	556	181	14696 ✱
14				582	582	587	581	576	577	595	620	639	667	685	686	643	638	623	603	591	583	569	557	560	553	575	565	602	0	11	42	709	21	23	545	164	14437 ✱
15				579	577	573	578	595	589	607	627	661	691	678	697	676	640	599	583	581	582	575	582	578	564	568	573	606	0	9	50	712	22	11	556	156	14553 ✱
16				589	575	580	579	578	582	597	608	651	669	671	685	681	667	630	608	589	577	575	582	571	575	580	580	607	0	11	45	702	20	33	567	135	14579 ✱
17				576	581	584	584	584	586	591	596	609	629	647	662	674	662	619	594	578	576	579	581	572	574	576	583	600	0	12	57	678	20	33	571	107	14397 ✱
18				582	583	586	585	590	600	612	639	663	687	695	712	680	643	643	620	604	569	537	557	562	503	460	425	597	1	11	14	732	23	27	406	326	14337 ✱
19			✓	480	504	472	505	498	483	493	493	511	525	548	588	585	589	558	538	516	534	536	541	556	554	547	557	530	2	11	39	610	0	00	421	189	12711 ✱
20				558	554	542	549	549	554	573	595	623	653	663	665	661	643	598	569	560	560	558	558	557	555	555	558	584	1	11	14	676	2	16	529	147	14010 ✱
21	✓			561	562	566	568	569	572	584	610	644	676	692	695	675	655	620	597	580	578	576	571	568	566	567	568	601	0	11	03	701	1	00	560	141	14420 ✱
22	✓			566	569	571	571	573	579	583	597	622	650	681	677	662	643	611	595	587	584	579	578	575	571	571	571	599	0	10	48	695	0	26	564	131	14366 ✱
23	✓	✓		573	573	575	576	578	581	594	618	647	682	705	708	686	647	609	598	591	592	589	585	583	581	578	582	610	0	11	09	715	1	13	571	144	14631 ✱
24				583	583	584	591	595	598	611	633	654	683	716	710	672	651	658	631	603	592	580	572	566	569	576	577	616	0	10	44	728	20	26	560	168	14788 ✱
25	✓			578	579	579	584	586	585	601	621	645	668	691	694	684	653	629	613	605	602	598	595	593	591	598	597	615	0	10	58	705	0	00	576	129	14769 ✱
26				598	598	597	598	596	598	601	623	663	700	688	730	702	688	664	623	586	558	544	541	542	545	556	567	613	0	11	19	761	19	34	535	226	14706 ✱
27	✓			571	578	583	583	584	585	595	607	619	627	635	643	645	634	620	611	608	601	587	579	580	582	584	584	601	0	12	22	648	0	18	567	81	14425 ✱
28	✓			586	587	591	596	598	601	601	609	636	663	691	702	696	680	649	621	614	606	596	593	594	591	591	594	620	0	11	22	705	0	00	582	123	14886 ✱
29	✓	✓		595	596	598	599	601	602	602	610	628	653	695	706	707	691	641	611	594	589	590	589	586	589	590	591	619	0	11	50	712	20	50	585	127	14853 ✱
30	✓	✓		591	594	598	600	600	600	605	614	621	643	669	684	695	681	644	621	606	597	586	584	583	586	587	590	616	0	12	07	700	20	00	581	119	14779 ✱
31																																					
MEANS ALL DAYS				574	575	576	577	579	580	589	606	627	652	672	682	675	654	625	601	586	578	571	573	573	569	566	568	601								161	
MEANS TEN DAYS ✱				578	580	583	585	586	587	594	608	629	654	680	688	681	661	628	608	598	594	588	585	583	582	583	584	610								122	
MEANS FIVE DAYS † (G. M. T.)				583	585	587	589	590	590	595	607	625	651	683	695	690	668	631	609	596	593	586 588	585 586	583	582	582	583	611									
MEANS FIVE DAYS ‡ (G. M. T.)				549	554	551	555	555	551	559	581	596	614	643	649	652	636	603	573	555	552	547	571	574	562	539	534	577									

DESIGNATIONS AND REMARKS
✱ = TEN LEAST DISTURBED DAYS
† = FIVE INTERNATIONAL QUIET DAYS
‡ = FIVE INTERNATIONAL DISTURBED DAYS
[ ] = APPROXIMATE MAGNETIC STORM
( ) = INTERPOLATED
⌈ ⌉ = ESTIMATED
▽ = LAMP OUT
△ = RECORD OFF SHEET
□ = CLOCK STOPPED
⊼ = NO RECORD

FIG. 33.—Specimen monthly tabulation of hourly mean values scaled from magnetograms.

consist of a magnetograph with certain additional special features to adapt the instruments to field-use and should be operated continuously in the same manner as the magnetograph at a fixed observatory. A portable observatory is now being constructed by the United States Coast and Geodetic Survey. The variometers will be insulated carefully against changes in temperature by suitable non-magnetic housings. The housings will be provided with double (optical) glass windows, with intervening air-spaces between the variometers and the recorder so that photographic registration may be accomplished and so that it will be unnecessary to disturb the instruments each day at the time of changing the records. The whole magnetograph is to be housed in a non-magnetic, weatherproof tent with dark-room compartment of black canvas surrounding the instruments. This compartment is provided with a light-trap for convenience in changing the records during daylight. In localities where reliable alternating-current electric power is available, the variometer-housing will be provided with electric heaters thermostatically controlled so as to operate the variometers at a constant temperature.

CHAPTER III

MAGNETIC PROSPECTING

C. A. HEILAND
Colorado School of Mines

I. INTRODUCTION

(1) GENERAL FEATURES OF MAGNETIC METHOD

The magnetic method of prospecting belongs to a group of geophysical methods in which "spontaneous" effects of geologic bodies are observed. It does not require the application of an extraneous field to produce a response from such bodies. This is an advantage from the point of view of field-application, but a drawback in the interpretation of results. Like the gravitational method, the magnetic method lacks depth-control; owing to the similarity of Newton's and Coulomb's laws, both methods give the integral effects of geologic bodies at such depths as are in the range of the instruments. A consequence of this is that the size of geologic bodies has to increase in proportion with their depths to be detectable.

The object of measurement in magnetic prospecting is the Earth's magnetic field. It is uniquely defined by the length and direction of the total-intensity vector. In terrestrial-magnetic research, such as is conducted in observatories and land and marine surveys, this vector is generally determined completely. For the ease and accuracy of measurement, intensity and direction of the total vector are not measured directly but instead suitable intensity and angular components of the vector. In recording at observatories, these components may be the three rectilinear intensities, X, Y, and Z; in surveys on land it is most convenient to measure D, I, and H (where X is the astronomic north, Y the astronomic east, Z the vertical component, D the declination, I the inclination, and H the horizontal component in the magnetic meridian). For the practical requirements of magnetic prospecting such detailed analysis is not necessary. Generally, one component only is measured; it is advantageous to select such a component as will bear the closest relationship of anomalies and position of geologic bodies. In the Northern Hemisphere where most magnetic prospecting has been conducted this component is the vertical intensity. Next follows the horizontal intensity whose anomalous values may be combined with the vertical-intensity anomaly to give the resulting disturbance-vector in the plane of the disturbed magnetic meridian. For certain mining applications of the magnetic method, it is advantageous to measure the horizontal component at right angles to the strike of the geologic feature investigated.

Intensity-values observed are expressed in gauss, Γ. Intensity-anomalies are generally stated in gammas, γ (1γ is one-hundred-thousandth part of a gauss).

As in other geophysical methods the application of magnetic prospecting depends on the existence of a difference in subsurface physical properties as well as on the magnitude of this difference. The physical property involved in magnetic prospecting is the magnetic susceptibility of rocks. Rocks may be divided into two major groups in regard to their magnetic effects, namely, strongly and weakly magnetic rocks. Strongly magnetic rocks include iron-ores and igneous and metamorphic rocks; most sedimentary rocks are but weakly magnetic.

Experience obtained in the practical application of the magnetic method in the past 10 to 15 years has indicated that it is the simplest, least expensive, and fastest method; that it may yield quantitative results provided geologic conditions are suitable, but that it must be supplemented by other geophysical methods where the structural consistency of the magnetic anomalies is doubtful.

(2) HISTORICAL DEVELOPMENT

The history of magnetic prospecting is intimately associated with, and is an outgrowth of, the development of the science of terrestrial magnetism. In this science, fundamental discoveries of its most important elements date back to the fifteenth, sixteenth, and seventeenth centuries—such as the discovery of the declination (1451), inclination (1546), secular variation (1634), and daily variation (1683). This was followed by a period of rapid development of instruments and methods, guided by such investigators as Gilbert and Gauss and by the organizations of magnetic research institutions in the major countries of the world. In the United States a division of Terrestrial Magnetism was organized by the United States Coast and Geodetic Survey, in 1899, and by the Carnegie Institution of Washington, in 1904. Magnetic prospecting in mining and in structural oil-exploration has followed a different trend of development. The use of magnetic instruments in mining was mentioned by Agricola in his "De Re Metallica." The first use of magnetic instruments in prospecting probably took place in Sweden about the year 1640. Swedish investigators such as Ask and Thilas made important contributions to the development of magnetic prospecting in mining around 1750. Thalén and Tiberg became famous for their instrumental and theoretical developments around 1870. On this Continent the dip-needle was introduced as early as 1750, but it was not until 1870 that data regarding its use were published. In 1899 Smyth published a detailed study of the application of magnetic methods. Other important dates in the development of magnetic prospecting in mining were the magnetic survey of the Kursk Anomaly, begun by Lazareff in 1917, the discovery of the magnetic effect of gold-placers by Gibson in 1922, and the intensive application of the method at its present state of technique since 1927.

Structural magnetic prospecting had a comparatively late start. Magnetic anomalies of various types of geologic structures were obtained first as a by-product of regional magnetic surveys conducted in various countries of the world since 1850. A different trend began in 1915 with the construction of the vertical field-balance by Adolf Schmidt, which since then has developed into the major instrument used in applications to structural magnetic prospecting. Its use for the location of salt-domes was first established by Schuh in 1920. It was introduced into this country in 1923. From 1926 to 1930 magnetic prospecting developed intensively in the oil-districts of the United States. Since 1930, its application as a major structural prospecting method has been reduced considerably, but it still finds much application as a reconnaissance-method to designate areas for more intensive study by other geophysical methods.

(3) APPLICATIONS OF MAGNETIC PROSPECTING

The great majority of magnetic anomalies is due to igneous rocks, iron-ores, and such sedimentary rocks as have derived their magnetite content from igneous rocks. Therefore, magnetic methods can be applied directly where the commercial mineral is strongly magnetic as in the case of magnetite, pyrrhotite, etc. Indirect applications of the magnetic method, however, far exceed the direct applications. In oil-exploration, the applications are in reality of a double indirect nature. First, oil cannot be found magnetically; we must rely on finding favorable structures in such formations as are expected to be oil-bearing; secondly, inasmuch as these formations are mostly non-magnetic, we must attempt to find igneous rock which bears a known structural relation to the potential oil-formations. Such applications are the mapping of buried hills of igneous or crystalline formations, the location of anticlines whose cores are made up of igneous rocks, and the location of faults which have displaced igneous or crystalline formations. Structural mapping, likewise, has applications in mining areas. Of a similar indirect nature is the location of non-magnetic ore-bodies in mining when associated with magnetite or pyrrhotite.

A brief summary is given below of all these applications, arranged in approximate order of importance. There are ten items, each of which includes a statement concerning the chief field of application, that is, oil, mining, or engineering geology.

OUTLINE OF APPLICATION OF MAGNETIC METHODS

- (*a*) (Oil) Location of buried hills
  - (1) If they are composed of granites, gneisses, or schist.
  - (2) If there are intrusions of igneous or metamorphic rocks.
- (*b*) (Oil) Location of anticlines
  - (1) If the magnetic basement members are uplifted together with the sedimentaries.
  - (2) If some of the folded formations are magnetic (contain iron-conglomerates, lava-flows, ferruginous sandstones, sands, or shales).
- (*c*) (Oil, mining) Location of faults
  - (1) If the basement is displaced.
  - (2) If magnetic members are interbedded.
  - (3) If the fault-fissure contains igneous sheets.
  - (4) If the formations adjacent to the fault have different magnetic characteristics.
- (*d*) (Mining) Location of igneous intrusions, igneous dikes, and contact-metamorphic zones.
- (*e*) (Mining) Location of iron-ores, magnetite, and hematite.
- (*f*) (Mining) Location of non-magnetic ores if associated with magnetite, pyrrhotite, or contained in lava-flows (location of gold, sulphides, copper).
- (*g*) (Oil, mining) Location of concentrates
  - (1) Of noble minerals (gold, platinum) if associated with magnetite concentrations.
  - (2) Of oil-bearing shoestring formations, if associated with magnetite.
- (*h*) (Oil) Location of salt-domes surrounded by glacial formations
- (*i*) (Mining) Location of meteorites
- (*j*) (Engineering) Location of buried magnetic objects, ammunition, pipe-lines, etc.

II. MAGNETIC PROPERTIES OF ROCKS

(1) DEFINITIONS

As in other industrial applications of magnetic research where the qualities of magnetic materials are involved, the main property designating the magnetic effects of rocks, minerals, and formations is the magnetic permeability. In addition to permeability, the term susceptibility is used in describing the magnetic properties of rocks. Both of these characteristics express the magnetization which a rock or formation acquires owing to induction in the Earth's magnetic field. In addition to the induced magnetization, magnetic anomalies are affected by the residual magnetization which a rock may have acquired from causes other than induction of the Earth's field. Two characteristics are generally used to describe the residual magnetization, namely, (1) the intensity of residual magnetization or the residual induction and (2) the coercive force.

The term "permeability" expresses the ratio of induction and field-lines. If condensation of lines occurs, the substance is paramagnetic and the permeability is greater than one; if divergence occurs, the permeability is smaller than one and the substance is called diamagnetic. The term susceptibility is related to the intensity of magnetization; the intensity of magnetization is the magnetic moment of the unit of volume and susceptibility is the ratio of the intensity of magnetization to the undisturbed field. Hence, the relation between permeability, μ, and susceptibility, κ, is

$$\mu = 1 + 4\pi\kappa$$

The susceptibility of the vacuum is 0; paramagnetic substances have a positive and diamagnetic substances a negative susceptibility. Rock-susceptibilities are generally expressed in 10^{-6} unit. This will be referred to hereafter as "susceptibility-unit" (Susc. U.). Both induced and residual magnetization may be obtained from a hysteresis-curve of a mineral or rock. Contrary to metallurgical practice, these hysteresis-curves are generally drawn for intensity of magnetization as function of field-strength; residual magnetization is then the magnetization for the field-strength zero, and coercive force is the negative field required to reduce the intensity of magnetization to zero.

(2) METHODS FOR DETERMINING MAGNETIC PROPERTIES

Methods for determining magnetic properties may be divided into two groups, corresponding to their usual order of application. First, a preliminary test is made to determine the proportions of residual and induced magnetization. Second, quantitative determinations of induced magnetization in the Earth's field as well as in fields greater than that of the Earth may be made.

Assuming that the vectors of induced and residual magnetization are oriented in the same or reverse direction, a *qualitative determination* of their relative amounts may be made by placing a rock-specimen close to a magnetometer and by reading the deflection, reversing the sample and reading the magnetometer again. It then follows that the induced magnetization is equal to a constant times the sum of the two deflections, while the residual magnetization is proportional to the difference of the two readings.

After residual and induced magnetizations have been determined qualitatively, the corresponding parameters of susceptibility and coercive force may be determined quantitatively by two types of methods: In the first group, measurements are made in the Earth's magnetic field; in the second group, the specimens are used in solenoids and positive and negative fields are applied.

One of the methods using the Earth's magnetic field is known as the *"test-tube" method.* The rock-specimen is pulverized and inserted into a test-tube of known volume. The tube is placed close to a magnetometer and the corresponding deflection observed. Then the susceptibility is equal to the tangent of the angle of deflection multiplied by the horizontal intensity of the Earth's magnetic field and a constant depending on the volume and distance of the test-tube. Another method using the Earth's magnetic field has been proposed by Koenigsberger [473] in which the magnetic specimen, in solid and tabular form, is placed close to one of the poles of the magnetometer's needle and the attraction is observed between the magnetic pole and the image produced by it in the specimen. The magnetic susceptibility is then equal to the magnetic intensity read on the magnetometer multiplied by the square of the distance of the surface of the sample from the magnetic pole and by a constant, divided by the pole-strength of the magnetic needle. The apparatus may be calibrated by an iron chloride solution of known concentration and density.

The writer has proposed a method [1402] to make susceptibility-determinations in the Earth's field independent of magnetic variations and shape of the specimen. An astatic magnetometer is employed for the purpose. A cast is made of the specimen from a material of known susceptibility. This and the specimen are placed on opposite sides of the lower magnet of the magnetometer at equal distances. The reading obtained is proportional to the difference in susceptibility of the specimen and the standard.

Susceptibility-determinations in fields greater than the Earth's field give more detailed information because they permit the plotting of a complete hysteresis-curve. The following methods come under this heading: Torsion-balance method, balance-method; inductive, solenoid-deflection, and ballistic methods.

In the *torsion-balance* method the specimen is pulverized, enclosed in a test-tube suspended at the end of one arm of a torsion-balance which is exposed to the attraction of a strong electromagnet. The susceptibility is equal to a constant multiplied by the deflection-angle divided by the square of the current of the electromagnet and the volume of the specimen.

In the *balance-method* a cylindrical sample is suspended from one end of a scale between the poles of an electromagnet. The specimen is first balanced with weight; current is then turned on and balance reestablished by an addition of weights. For a long sample the susceptibility is equal to twice the weight added (in dynes), divided by the square of the field at the lower end of the sample.

The *inductive methods* are based on the fact that the inductance of a coil and the energy-transfer in a transformer depend on the magnetic permeability of the core-material.

In Stutzer's method two air-core transformers are used whose primaries are connected in series aiding to an ammeter, chopper, and battery, while the secondaries are connected in series opposing through a galvanometer and commutator mounted on the same shaft with the chopper. The coils are balanced so that when a pulsating current is sent through both primaries, no current flows in the secondary when there is no specimen in the test-coil. The balance is disturbed when a sample is inserted. The galvanometer-deflection is proportional to the susceptibility of the sample.

Instead of using pulsating direct current, Barret [1402] employs a single impulse through two induction-coils whose secondaries are connected to a ballistic galvanometer. Before the sample is inserted the two coils are balanced either inductively or galvanically. In another method Barret employs a modified form of an inductance-bridge with alternating current of 60 cycles.

The principle of *solenoid-deflection* methods is the determination of the deflection of a magnetometer by a solenoid containing the specimen. The magnetic effect of the solenoid may be balanced by a second solenoid on the other side of the magnetometer at the same distance. In each case the deflection of the magnetometer is directly proportional to the susceptibility of the specimen in the various fields.

Ballistic methods are based on the fact that the induction-current produced in a coil by pulling a magnet through it rapidly is proportional to its magnetic moment.

(3) NUMERICAL DATA

Numerical data on properties of magnetic rocks will be given in two groups, namely, (1) data on susceptibilities and (2), data on coercive force [479].

The magnetic susceptibilities of minerals fall into four distinct groups. Rock-forming minerals range in susceptibilities from −8 Susc. U. for graphite to about 130 Susc. U. for augite. Ore-minerals (with the exception of iron-ore) range from 4 Susc. U. for pyrite, to several hundred units for other sulphides. At the top of the list is pyrrhotite giving exceptionally high values up to 100,000 and even one-half-million units.

In the third group, iron-minerals, particularly those of the hematite-limonite group, have susceptibilities from 50 to 200 Susc. U. Some hematite, however, may reach a susceptibility of 1,000 to 3,000 Susc. U.

Magnetite has been placed in a fourth group owing to the extreme variations of susceptibility observed. For magnetite-ores the susceptibilities are generally of the order of 100,000 to one-fourth-million units, which, in some localities, may reach one million to one and one-half million. Crystals may vary in susceptibilities from 10 to 20 million units.

As to rocks, three groups may be distinguished depending on susceptibilities and lithological character, namely, (1) sedimentary, (2) metamorphic, and (3) igneous rocks. The susceptibilities of sedimentary rocks range from several negative units for anhydrite, gypsum, and rock-salt, to several tens of units up to 100, at the most, for ferruginous sandstones. Metamorphic rocks range higher in susceptibilities, generally of the order of several hundred to several thousand units. Igneous rocks, in their magnetic behavior, are very similar to metamorphic rocks, basic rocks being much more magnetic than acidic rocks. Probably the most magnetic igneous rock is basalt or dolerite whose susceptibilities may go up to some 10 to 15 thousand units.

Data on coercive forces are not very abundant in the literature. Most of those available refer to magnetite and magnetite-ores whose coercive forces range from around ten to about 100 gauss. Little is available on coercive forces of sedimentary and metamorphic rocks; the values so far observed seem to indicate coercive forces from several gauss to around 200 gauss. Coercive forces of igneous rocks vary from several gauss to 100 and to a maximum of about 200 for basalt.

(4) FACTORS DETERMINING ROCK-MAGNETIZATION

Factors determining rock-magnetization are twofold, namely, (1) the nature of their constituent minerals and (2) geologic history. In regard to mineral composition it is not the iron-content which determines the magnetization but the valency of the iron oxide. Hence, magnetization depends chiefly upon the amount of magnetite present in the rock. Next in order is pyrrhotite. Probably also ilmenite and titanomagnetite may affect susceptibility, although the data available in the literature on this subject are very conflicting. The size of the magnetite-grains is likewise of decided influence. Rocks containing fine-grained magnetite have a lower susceptibility than rocks containing coarse-grained magnetite. Another important relation is that generally the basic rocks, both volcanic and plutonic, are more magnetic than the intermediate and acidic types. Plutonic rocks, being coarse-grained, are generally more magnetic than the volcanic rocks with the exception of basalt, and within the volcanic rocks the younger group is more magnetic than the older group.

Of the geologic factors affecting rock-magnetization in the course of geologic history, it is well known that exposed magnetic rocks may be magnetized to high values by lightning. The opposite effect is produced by changes in temperature which the rocks undergo in the course of their geologic history. Stresses occurring in mountain-building, faulting, folding, and epeirogenic movements affect the magnetization of formations although little is available on this point in the literature.

Disintegration results in breaking down the magnetic trivalent ion into the less magnetic bivalent ion; in addition to the chemical effect, there is a mechanical effect of disintegration which results in a reduction of size of particle of magnetite and thus reduction in susceptibility.

Another geological factor, concentration, has the opposite effect of disintegration. It may be of a chemical and mechanical nature. Outstanding examples of increases of magnetization by concentration are accumulations of magnetite in contact metamorphic zones and of black sands in gold-placers and shoestring oil-formations.

Finally, after geologic bodies have become magnetized, their position may be changed by structural forces affecting the Earth's crust; similar effects are produced by over-turning of solidified portions of basalt in the plastic flow of the magma.

III. MAGNETIC INSTRUMENTS

(1) CLASSIFICATION—GENERAL THEORY

Owing to the fact that the magnetic prospecting-method is one of the oldest geophysical methods, instruments of a great variety of construction have been developed. According to application, magnetic instruments may be grouped into (1) prospecting magnetometers, (2) magnetic theodolites and related instruments used in regional surveys, (3) observatory-instruments.

According to principle of construction, magnetic instruments can be divided into two groups, namely, (1) instruments for the determination of the *direction* of the total or partial field-vectors and (2) instruments for the determination of the *intensity* of the field or its components.

In the first group of instruments the direction of a component may be determined: (1) By observing the rest-position of the magnet capable of rotation about a vertical axis (declinator) and about a horizontal axis (inclinator, dipping needle); (2) by determining the position for zero-induction of a rotating coil; and (3) by calculating direction from intensity-ratios.

More important for our purposes are the instruments for the determination of intensity-components. Instruments of this type may be divided into four groups. In the first, intensities are obtained by measuring the period of oscillation of a magnet about its zero-position; in the second, intensities may be derived from induction-observations with rotating coils; in the third, by measuring the induction in soft-iron bars; and in the fourth, by using a comparison of the magnetic element with some other known constant force.

This last type of instrument is of greater importance in prospecting magnetometers than the three types previously mentioned. In practice, four kinds of comparison forces may be used: (1) Magnets or coils; (2) elastic forces; (3) gravity; and (4) the kinetic energy of electrons.

It is possible to give a general theory of all types of magnetometers by setting up equations for the effect of the Earth's magnetic field upon a magnetic needle moving freely in space and by combining these with a second set of equations involving whatever comparison-forces may be used to measure the magnetic effects; in most prospecting magnetometers the comparison-force is gravity. For the derivation of the fundamental equations, we assume that the total Earth's magnetic field is represented by three rectilinear components (see Fig. 1) designated by X', Y', and Z'. The moving system of the components acting on this system may be represented by x, y, and z. It may be further assumed that this needle oscillates in a plane ABC which dips below the horizon by the angle, ι, and whose intersection with the horizon has the azimuth, α, from astronomic north. The position of the north pole of the magnetic needle on this plane is given by the angle, η.

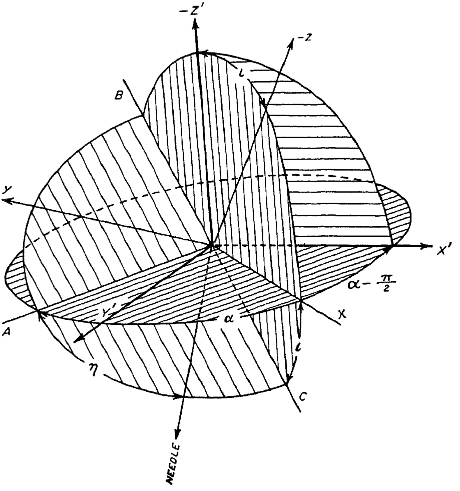


FIG. 1.—Forces acting on a magnetic system free to move in plane ABC.

Then the components acting on the needle are given by equations (1) as function of the stationary components.

$$\left.\begin{aligned} x &= X'(\cos\alpha\cos\eta + \sin\alpha\sin\eta\cos\iota) + \\ &\qquad Y'(\sin\alpha\cos\eta - \cos\alpha\sin\eta\cos\iota) + Z'\sin\eta\sin\iota \\ y &= X'(\cos\alpha\sin\eta - \sin\alpha\cos\eta\cos\iota) + \\ &\qquad Y'(\sin\alpha\sin\eta + \cos\alpha\cos\eta\cos\iota) - Z'\cos\eta\sin\iota \end{aligned}\right\} \quad (1)$$

$$z = -X'\sin\alpha\sin\iota + Y'\cos\alpha\sin\iota + Z'\cos\iota$$

Since the forces acting on the north and south pole balance one another and inasmuch as the z-component, if a needle is suspended in bearings, is neutralized by the pivot-pressure, we may put $z = 0$ and $x = 0$. Furthermore, the coordinate system may be so rotated that α becomes the magnetic instead of the astronomic azimuth. Then $X' \equiv H$, $Y' = 0$, $Z' \equiv Z$, and the torque on the magnetic needle equals $D_1 = My$ where M is the total magnetic moment of the magnetic system. Hence, equations (1) become

$$D_1 = M[H(\cos\alpha \sin\eta - \sin\alpha \cos\eta \cos\iota) - Z \cos\eta \sin\iota] \tag{2}$$

This is a universal formula for virtually all magnetic instruments controlling the moment on a needle free to move in an arbitrarily oriented plane.

If the same needle is subjected to the effect of gravity, the gravity-moment is

$$D_2 = -emg \cos\eta \sin\iota \tag{3}$$

where e is the distance of the center of gravity from the axis of rotation, m is the mass of the system, g is gravity, and η and ι are angles whose significance may be obtained from Figure 1.

If the direction of e does not coincide with the x-axis, but makes an angle with the same so that it is split up into a component a in the x-axis, and d in the y-axis, equation (3) becomes

$$D_2 = -mg \sin\iota(a \cos\eta + d \sin\eta) \tag{4}$$

When the two moments for the magnetic and gravity effects are combined, equation (5) is obtained.

$$\tan\eta = \frac{MH \sin\alpha \cos\iota + MZ \sin\iota + mga \sin\iota}{MH \cos\alpha - mgd \sin\iota} \tag{5}$$

This is a fundamental formula for all magnetic instruments which are based on the comparison of gravity and magnetic forces, and, therefore, a formula which is chiefly applicable to the Schmidt vertical- and horizontal-field balances.

(2) SCHMIDT VERTICAL AND HORIZONTAL BALANCES

(a) *Vertical balance*

In this instrument (see Fig. 2) a magnetic system is balanced on a knife-edge at right angles to the magnetic meridian. Its deflections are measured by means of an autocollimational telescope-system. The center of gravity is so adjusted that it is on the south side below the axis.

The balance-system is surrounded by a case which contains copper dampers and thermometers. Around the metal case in turn is placed a cork-lined jacket to protect the interior against excessive variations of temperature. The magnetic system is supported by a bridge equipped with two quartz pieces ground into semi-cylindrical form which act as bearings for the quartz knife-edge on which the system is supported. A positive clamping-mechanism is provided. The instrument is attached to a tripod by means of three pegs fastened into the bottom of the case. The deflections are read by observing the relative displacement of two scale-images in all models up to 1935. In the earlier instruments the scale has 40 divisions—the center or 20-division mark being used as the index on the stationary scale. In the optical system of the new instruments only one scale of 60 divisions is provided; the position of a pointer reflected from the mirror of the magnetic system is read on this scale.

The earlier magnetic system consists of two magnetized bars attached to an aluminum cube. This cube carries a knife-edge, mirror, two lateral screws, and one vertical screw. The two lateral screws are for latitude adjustment; the vertical screw is for scale-value adjustment. In the newer instruments, temperature-compensated systems [1408] are used consisting of a steel frame holding the knife-edge; to its top, a mirror is fastened; its sides hold two spindle made of aluminum and invar to obtain temperature-compensation. The scale-value adjustment screw is similar to the one used in the old-type system. The top of the tripod is provided with a graduated scale so that the instrument may be oriented into any desired azimuth. Before the instrument is placed on the tripod, a compass is used to determine the magnetic meridian or the normal thereto. An extension of the tripod-head carries a tube for auxiliary magnets.

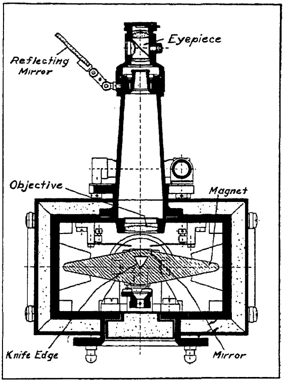


FIG. 2.—Schmidt vertical magnetometer.

For the Schmidt vertical magnetometer we may substitute in equation (5)

$$\tan 2\eta = (s - s_0)/f$$

where s_0 is the center reading, or reading 20, corresponding to the deflection 0, and s is the reading corresponding to a deflection η; f is the focal length of the objective lens. For $\tan 2\eta$, $2 \tan \eta$ may be substituted with sufficient approximation so that the equation for the reading is

$$(s - s_0) = 2f\frac{MH \sin \alpha \cos \iota + MZ \sin \iota + mga \sin \iota}{MH \cos \alpha - mgd \sin \iota} \tag{6}$$

In the position of use of the vertical balance, α is 90° or 270° and ι is equal to 90°. Furthermore, a and d are negative, the center of gravity being on the south side below the axis so that equation (6) becomes

$$(s - s_0) = 2f(MZ - mga)/mgd \tag{7}$$

Substituting the "scale-value"

$$\epsilon = mgd/2fM \tag{8}$$

we obtain from equation (7)

$$\epsilon(s - s_0) = Z - (m/M)ga \tag{9}$$

which expresses clearly that, when the deflection in scale-divisions is multiplied by the scale-value, the difference of vertical intensity and gravity action is obtained. In fact, the last term on the right side of the equation, $(m/M)ga$, is the vertical intensity Z_0 for which the magnetic system has been adjusted. Therefore, multiplication of scale-value by scale-reading from 0, gives the *anomaly* in vertical intensity.

Brief mention must be made of a number of effects which interfere with the accuracy of observations if the instrument is not applied properly. The magnitude of errors arising from these effects may readily be obtained from the theory.

If the instrument is not orientated properly into the magnetic east-west or west-east position, the reading will change, because the scale-value changes. If the instrument is rotated from the east-west position to the north, the reading will increase; if it is rotated to the south, the reading will decrease provided that the reading is less than 20. If the reading is greater than 20, rotation to the north will produce a decrease and a rotation to the south will produce an increase. The change in scale-value is given by

$$\epsilon_\delta = \epsilon_0 \mp H \sin \delta/2f \tag{10}$$

where δ is the angle of misorientation from east to west. On a location of known horizontal intensity this equation may, therefore, be used to determine the sensitivity of the instrument without requiring auxiliary magnets or deflection-coil. The effect of misorientation on a vertical magnetometer is small because the vertical intensity is present throughout a complete circle of revolution.

The effect of incorrect leveling of the magnetometer on the reading is quite complex for two reasons: (1) Because the east-west component of tilt is effective optically while the north-south component is effective magnetically; (2) because the effect differs depending on whether the axis of revolution is inclined in this direction or whether the case on a properly leveled tripod-head is inclined. The east-west component of an inclination of the axis of revolution causes a difference in the readings obtained in the east and west positions. This, however, cancels out in the average of the east and west readings. If the case is inclined, that is, if the instrument has not been placed properly on the tripod-head, no differences in the two readings will be produced and, therefore, the error resulting therefrom may go undetected. If the axis of revolution of the tripod is tilted in the north-south direction, the horizontal intensity will become effective and produce a deflection which is the same in both positions. If, on the other hand, the instrument-case is tilted in the north-south direction, or if there is a difference in elevation of the two quartz bearings, the horizontal intensity will again bring about an error that in this case is positive when the north pole is in the east and negative when the north pole of the system is toward the west, so that this error cancels in the mean of the two observation-positions. From the standpoint of practical operation of the instrument, the instrument must be most carefully leveled in the direction of the magnetic meridian and, furthermore, must be most carefully placed in a level position on the tripod-head in the east-west direction.

With the vertical magnetometers, auxiliary magnets may be used for scale-value determinations and for extending the range of the instrument. They are situated in the first Gauss position and therefore the change in vertical intensity brought about is [see equation (12) for symbols]

$$\Delta Z = \pm 2M_a k/r^3 \qquad (11)$$

Although the Schmidt magnetometers are based on a comparison of magnetic intensity with gravity, such gravimetric changes as occur with latitude- and gravity-anomalies are so small compared with the absolute value of gravity that the accuracy of the instrument-readings is not affected.

The effect of temperature on a magnetic system is fairly complex. The main effect of a rise in temperature is to lower the moment of the magnetic system and thereby to cause the north pole of the system to rise which results in an apparent decrease of vertical intensity. This may be partially compensated, in the old magnetic system, by an arrangement of steel blades with reference to the aluminum body in such manner that with a rise in temperature the center of gravity is moved toward the north side of the system. However, complete compensation cannot be realized with an old-style magnetic system. In the new-style compensated system an aluminum spindle carrying a bronze weight is located on the north side of the frame. The position of the weight can be so adjusted as to obtain full temperature-compensation for a given magnetic latitude [1408].

From some of the equations stated previously for the deflection of a vertical balance, the effects produced by changes in the center of gravity of the magnetic system and by changes in its magnetic moment may be readily evaluated, showing the necessity of handling and transporting the instrument with extreme care if consistent results are desired. For instance, it can be shown that a change of five γ in the reading will be brought about by a displacement of the center of gravity equal to one-millionth cm in a horizontal direction. The same change in scale-value will be produced by a change in the vertical position of the center of gravity by one-thousandth cm. By a drop in the magnetic moment of the magnetic system of one gauss, the reading will decrease by 35 γ.

Calibration of the instrument and determination of its constants do not require much additional equipment. Scale-values are generally determined by auxiliary magnets or Helmholtz coils. Temperature-coefficients are measured by placing the instrument in an electrically heated container which fastens on the tripod of the standard instrument. The formula for scale-value determinations by means of auxiliary magnets is

$$\epsilon = 4M_a k/(s_2 - s_1)r^3 \tag{12}$$

where M_a is the moment of the auxiliary magnet, k is a deflection-constant, and r is the distance of the center of the magnet from the magnetic system, and s_1 and s_2 are the readings observed with the north pole of the magnet up or down, respectively. For deflection-observations by means of Helmholtz coils, equation (12) changes to

$$\epsilon = 2iC/(s_2 - s_1) \tag{13}$$

where C = coil-constant and i = current.

Field-procedure in applying the magnetometer consists of taking three readings, interrupted by clamping and releasing in the east position, and the same number of readings in the west position, after the instrument has been carefully leveled and orientated. The readings are averaged and a base-reading is subtracted as obtained at a station with presumably normal value of the magnetic vertical intensity. To this the temperature-correction, auxiliary-magnet correction, and base-correction are added or subtracted, respectively. The value of the base-correction is obtained from the evaluation of the error of closure when checking back on a base-station.

(*b*) *Horizontal balance* [124]

The mechanical arrangement of the horizontal balance is virtually the same as the one in the vertical balance. The magnetic system, however, is suspended with its blades in a vertical position and readings are taken in the magnetic meridian. This is possible in one position only; the instrument cannot be rotated 180°; if this were done, gravity would be

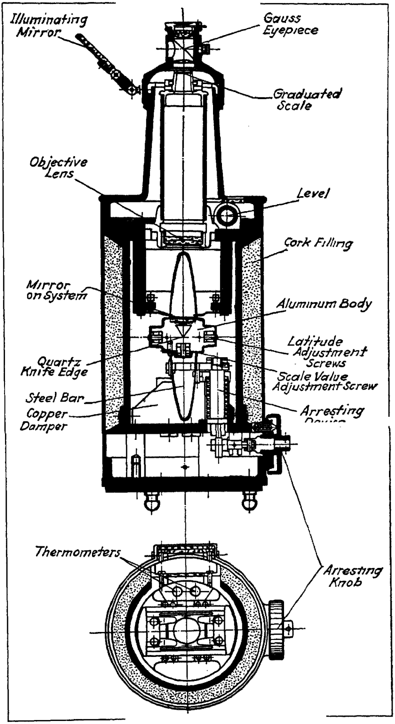


FIG. 3.—Schmidt horizontal magnetometer.

added to instead of subtracted from the magnetic couple, and thus the system would be thrown completely off balance. Figure 3 illustrates the horizontal magnetometer.

If φ is the deflection from the vertical position of the magnetic system, we obtain from equation (5), by substituting $(90 - \varphi)$ for η and interchanging a and d, the principal formula of the horizontal magnetometer as in equation (14).

$$\tan \varphi = \frac{MH \cos \alpha - mga \sin \iota}{MH \sin \alpha \cos \iota + MZ \sin \iota + mgd \sin \iota} \tag{14}$$

In the operating position where α is 0 and ι is 90°, we have

$$\tan \varphi = \frac{MH - mga}{MZ + mgd} \tag{15}$$

This may be written in terms of scale-readings

$$(s - s_0) = \frac{2f(MH - mga)}{MZ - mgd} \tag{16}$$

or

$$(s - s_0) = \frac{2fM}{MZ - mgd}\left(H - \frac{mga}{M}\right) \tag{17}$$

where $[2fM/(MZ - mgd)]$ is the reciprocal scale-value of the horizontal magnetometer and (mga/M) is the horizontal intensity H_0 for which the system is adjusted.

As in the case of the vertical magnetometer, a discussion of various effects follows.

Misorientation of a horizontal magnetometer is of much more serious consequence than misorientation of a vertical magnetometer, owing to the fact that the horizontal intensity is present, in its positive direction, in the magnetic meridian only and is zero at right-angles thereto. If s_α is the reading obtained in any azimuth α and ϵ_H is the scale-value of the horizontal balance, then the reading in any azimuth α is

$$(s_\alpha - s)(H/\epsilon_H)(\cos \alpha - 1) \tag{18}$$

From this it follows that misorientation always produces a decrease in the normal reading and that an error of only 40′ of misorientation will produce an error of one-tenth of a scale-division in a standard instrument.

Failure to level correctly a horizontal magnetometer is much less serious in this instrument than it is in a vertical magnetometer. The north-south component of a tilt of the instrument will produce merely an effect of an optical nature; tilt in the east-west direction will produce very little change, because it will affect only the action of gravity.

Auxiliary magnets are used with this magnetometer in the second Gauss position so that the formula for the scale-value as determined by a magnet M_a would be

$$\epsilon_H = 2M_a k'/(s_2 - s_1)r^3 \tag{19}$$

where k' is a deflection-constant (the deflection-constant for the second Gauss position, not being the same as the one for the first Gauss position).

From equation (17) it is evident that the scale-value of a horizontal magnetometer depends on the magnetic vertical intensity; hence, the change in scale-value when the vertical intensity changes is equal to

$$\Delta\epsilon = \Delta Z/2f \tag{20}$$

from which the change in horizontal intensity follows as in equation (21).

$$\Delta H = (\Delta Z/2f)(s - 20) \tag{21}$$

As vertical-intensity observations are usually made in connection with horizontal-magnetometer measurements, this correction may readily be applied.

Changes in gravity are again without noticeable effect on readings taken with the horizontal magnetometer.

Effect of temperature on the horizontal magnetometer is, in principle, identical with its effect on the vertical magnetometer. As the temperature increases, the magnetic moment of the system will be reduced, resulting in an apparent decrease of horizontal intensity. This may be compensated partially by a suitable arrangement of the blades in the magnetic system or by using a compensated horizontal-magnetometer system whose construction is similar to the temperature-compensated system used in the vertical magnetometer.

As to the calibration of the instrument, the procedure of scale-value and temperature-correction determinations follows the same principles as stated for the vertical magnetometer.

In field-application, the tripod is set up, leveled, and orientated by means of a compass into the magnetic meridian. In this position three to six readings are taken interrupted by clamping and releasing of the magnetic system. These readings are averaged; the base-station reading is subtracted, the difference is multiplied by the scale-value of the observed anomaly and is corrected for temperature, diurnal variation, and base-correction.

(3) HOTCHKISS SUPERDIP

This instrument is intended essentially for the measurement of total intensity. As shown in Figure 4, a magnetic system is suspended on a horizontal steel axle on agate bearings in the magnetic meridian. Fastened to the steel blade is a counterarm whose angle ζ with the magnetic axis may be varied. Attached to this counterarm is a small mass m'. In the theory given below it will be shown that the position of this weight on the arm determines essentially the latitude-adjustment of the magnetic system, while the angle which the arm makes with the magnetic axis controls primarily the sensitivity of the instrument. By removing the counterweight m' and assuming symmetrical mass-disposition about the axis of rotation, the instrument can also be used for the determination of inclination. However, in field-practice it is inconvenient to remove and replace the counterweight at every station; if measurements of inclination are desired, it would be more advantageous to use two magnetic systems. Most operations are confined to determinations of the total intensity.

In Figure 4, T signifies the total intensity, I the inclination, Φ the deflection of the needle from a zero-position at right-angles to the direction of total intensity, ζ the angle of the counterarm with the magnetic axis, Ψ its angle with the horizontal when the deflection is Φ, and $\xi = \Psi + \Phi = 90 - I - \zeta$. Then the angle η used in previous equations corresponds to $(90 - I - \Phi)$. Equation (2) is then applicable and for the Hotchkiss superdip where $\alpha = 0$ and $\iota = 90°$, we have

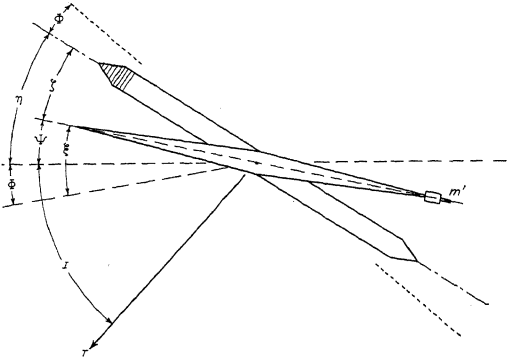


FIG. 4.—Action of Hotchkiss superdip.

$$D_1 = MH \sin (90 - I - \Phi) + MZ \cos (90 - I - \Phi) \qquad (22)$$

For the gravity-moment we have

$$D_2 = -em'g \cos \Psi \qquad (23)$$

or

$$D_2 = -em'g \cos (\xi - \Phi) \qquad (24)$$

As in the condition of equilibrium $(D_1 + D_2) = 0$ it follows from equations (23) and (24)

$$\tan \Phi = \frac{MH \cos I + MZ \sin I - em'g \cos \xi}{MH \sin I - MZ \cos I + em'g \sin \xi}$$

and by substituting $\cos I = (H/T)$, $\sin I = (Z/T)$, and $(H^2 + Z^2)/T = T$

$$\tan \Phi = \frac{MT - em'g \sin (I + \zeta)}{em'g \cos (I + \zeta)} \tag{25}$$

This is the main equation controlling the action of the Hotchkiss superdip. It is seen that if ζ exceeds the *critical angle* $(90 - I)$, the angle, Φ, will become 90°, that is, the system will swing into the direction of the inclination.

For two total intensities and two deflection-angles, equation (25) may be written

$$\tan \Phi' - \tan \Phi = M(T' - T)/em'g \sin \xi \tag{26}$$

or

where

$$\left.\begin{aligned} \epsilon\Delta\Phi &= \Delta T \\ \epsilon &= em'g \sin \xi/M \end{aligned}\right\} \tag{27}$$

is the scale-value of the instrument. From equation (27) it is evident that the sensitivity of the superdip depends on the angle which the counterarm makes with the magnetic needle.

(4) Miscellaneous other prospecting instruments [917]

Although the Schmidt balances and the Hotchkiss superdip are most extensively used at this time, there are a great many other magnetic prospecting instruments which can be used in place of them, particularly where the great sensitivity which these instruments furnish is not required.

In this group fall numerous types of Swedish prospecting magnetometers which were developed toward the end of the nineteenth century and are still used in many iron-ore districts. The simplest representative of these instruments is the *Swedish mining-compass* which consists of a magnetic needle so suspended from a stirrup that it may rotate about both horizontal and vertical axes. In other words, this instrument is a dipping needle with automatic meridian-adjustment. If the center of gravity coincides with the axis of rotation, the instrument will measure the inclination. If a counterweight, in form of a small piece of wax, is attached to the needle and so adjusted that for a normal vertical intensity the system is horizontal, the instrument will furnish essentially vertical-intensity anomalies, although no provision is made to obtain any of these quantities quantitatively. The action of the Swedish mining-compass may be obtained from equation (5) as

$$\tan \eta = (1/H)[-Z - (em'g/M)] \tag{28}$$

which may be written

$$\tan \eta = \Delta Z/H \tag{29}$$

or

$$\tan \eta = \tan I(\Delta Z/Z) \tag{30}$$

Both of these equations are in a form convenient to express the action of the instrument as a vertical-intensity magnetometer and inclinometer depending on the adjustment of the counterweight.

The *dip-needle* is a well known magnetic instrument for rapid reconnaissance [1419]. It consists of a magnetic needle mounted in a stirrup so that it may rotate freely about a horizontal axis in a vertical plane. Generally, the instrument is first held with the axis of rotation vertical and the meridian determined. Then the case is rotated about that axis so that the needle now oscillates in a vertical plane in the magnetic meridian. Then equations (29) and (30) apply; depending on the gravity-adjustment, the dip-needle will furnish either vertical intensity with horizontal intensity used as scale-value, or inclination with vertical intensity as scale-value. While this is the customary procedure, there is no need to complicate the behavior of the instrument in that manner as it may readily be used in a plane at right-angles to the magnetic meridian. In the magnetic prime-vertical, the horizontal intensity is zero and the instrument will give vertical-intensity anomalies only.

Another instrument for the measurement of vertical intensities which has been used extensively in mining is the *Thomson-Thalén magnetometer* [917]. It consists of a sensitive magnetic system rotating about a horizontal axis in a plane normal to the magnetic meridian. Mounted close to this system and underneath is a permanent magnet so that the effect of the normal vertical intensity on this system is compensated. The position of this magnet may be changed by a micrometer-screw; thus, vertical-intensity anomalies appear as readings of the distance of the compensating magnet from the magnetic system.

In the *Dahlblom pocket-magnetometer* [917] a compass-needle rotates about a rigid axis in either a horizontal or vertical plane depending on how the instrument case is held. The comparison-force is the torque of a helical spring. Both horizontal and vertical intensity may be measured with the instrument. In the well-known *Thalén-Tiberg magnetometer* [917], a compass-needle is suspended in a case in such manner that it may be used in a horizontal or vertical plane. In a vertical plane the instrument thus gives the inclination. When turned into the horizontal plane it is used with a deflection-arm and deflector, thus giving the horizontal intensity or horizontal-intensity anomalies, respectively.

There are a number of other magnetometers based on the deflection-principle, such as the De Collongue deflector, the Schmidt compensation-magnetometer, the Kohlrausch magnetometer, the Ostermeier universal magnetometer, the Wilson-Brunton compass-attachment, and the writer's

Cardan-suspension magnetometer, for descriptions of which the reader is referred to the literature.

Prospecting magnetometers based on other principles have also been suggested, such as the *magnetron* (a two-electrode vacuum-tube whose plate-current is critically dependent on an axial magnetic field), the magnetic torsion-balance which is a modification of the Eoetvoes *torsion-balance*, and the *earth-inductor gradiometer* [1415] in which electromotive forces induced in two coils rotating about a horizontal axis are compared by a bridge-arrangement, thus giving the horizontal vertical-intensity gradient. Modifications of the *earth-inductor* have been suggested and used as sensitive prospecting instruments. Depending on the orientation of its axis of revolution, an earth-inductor may be employed to measure any desired magnetic-intensity component as long as the speed of revolution is kept constant or the intensity compensated. The constant-speed principle utilizes a valve-maintained tuning-fork and synchronous motor to drive the inductor; in the compensation-instruments, the intensity-components to be measured may be reduced to zero by permanent magnets or by Helmholtz coils.

Finally, intensity-measurements have been made by using induction in *soft-iron or perminvar bars*. The instruments designed by Rieber and McNish utilize this principle.

(5) MAGNETIC THEODOLITES AND OBSERVATORY-INSTRUMENTS

These instruments are used for terrestrial-magnetic research in Government land-surveys and in recording magnetic variations at observatories. They were used for prospecting purposes at a time when prospecting magnetometers had not reached their present degree of sensitivity. They are of numerous types and are well described in the literature [see section *A-e* of Chapter XIII and Chapter II of this Volume].

IV. CORRECTIONS IN MAGNETIC PROSPECTING

The following effects have to be corrected for or eliminated, respectively, in magnetic prospecting: (1) Temperature; (2) magnetic variations; (3) planetary effects; (4) base-correction; (5) iron objects; (6) terrain-effects; and (7) normal values.

(1) TEMPERATURE

A temperature-correction must be applied in instruments that have no or but a partial compensation. This applies to both field- and observatory-instruments. Temperature-corrections may be avoided in compensated instruments, or in uncompensated instruments when used at low sensitivity, or in recording instruments when provision has been made to maintain constant temperature.

(2) MAGNETIC VARIATIONS

To what extent magnetic variations are considered in prospecting depends entirely on the accuracy desired. Work on iron-ore bodies and large magnetic anomalies due to other causes does not require consideration of magnetic variations. Next in accuracy is checking back at the base-station at frequent intervals and incorporating a variation-correction in the base-correction. Still more accurate is the use of daily-variation curves or tabulations which are available for various seasons of the year. Other methods stated in order of increasing accuracy are: (1) The use of tracings of curves of regularly established magnetic observatories; (2) visual observations on a second instrument every 10 to 30 minutes; (3) the use of a temporary observatory made up by using recording attachments instead of telescopes on regular field-balances.

Variations may be completely eliminated in the field by using two instruments at subsequent stations and reading them simultaneously. In stationary instruments used for determinations of temperature-coefficients, magnetic susceptibilities, etc., variations may be eliminated by the use of astatic systems.

(3) PLANETARY EFFECTS

Planetary effects are those produced by the normal variation of magnetic elements with latitude and longitude. They may be disregarded for small areas and large magnetic anomalies. Corrections may be obtained from magnetic maps published by the Government and research institutions.

(4) BASE-CORRECTION

This is a correction produced by variations in prospecting magnetometers as a consequence of transportation or demagnetizing fields. The base-correction is determined by checking back on a base or sub-base at least twice a day. If the error of closure is small, it may be evenly distributed among stations occupied between checks.

(5) IRON OBJECTS

Iron objects, power-lines, and similar interferences cannot be corrected for but must be avoided as much as possible. The following examples [1403] will help the observer to set his instrument a sufficient distance away from such interferences—the effects are given for a vertical magnetometer of normal sensitivity. (1) The effect of the instrument-case is approximately 125 γ at a distance of one yard and disappears at a distance of five yards. (2) A passenger automobile may be expected to produce a negative anomaly between 600 and 1,000 γ at three yards, the effect being negligible at a distance of 30 yards. (3) Wire fences running north and south may have a maximum effect of around 300 to 400 γ at one yard, which becomes zero at around a distance of 35 yards. (4) The effect of buried pipe-lines depends largely on diameter, thickness, and distance. The effect will probably be zero at distances of 25 yards. The maximum effect at two yards may be close to 500 γ. (5) A railroad will produce an effect of around 1,500 γ at ten yards, which will become zero at a distance of 125 yards. (6) The effect of well-casing will depend to a certain extent on its length. Its effect a few feet away from the well may readily be 50,000 γ. If the casing is short, negative anomalies will be found on the outside of a circle of positive anomalies. The negative anomalies may reach an amplitude of around 50 γ. At a distance of 90 to 100 yards, the effect of well-casing is generally negligible.

Other objects containing iron which have to be avoided are houses, bridges, slag road-beds, steel culverts, oil-tanks, well-derricks, and mine-shafts whose effects have been discussed by Kohl [1409-*A*].

Power-lines produce various effects on magnetic measurements. Trolley-lines run by direct current produce considerable magnetic variations particularly in the area between track and central power-station. Alternating-current lines, likewise, produce variations due to surges occurring with changes in power-consumption. Furthermore, they have in their vicinity a considerable demagnetizing effect on the instrument. Riding on electric trains and trolleys may produce excessive base-corrections.

(6) TERRAIN-EFFECTS

When the surface-rocks are non-magnetic, there nevertheless may be an effect of irregularities of terrain if the geologic bodies producing the magnetic anomalies are close to the surface. In such case, irregular terrain has the effect of changing the distance between effective pole and observer. This may give rise to considerable difficulties in interpretation. These may be partially avoided by graphical interpretation-methods, taking into account the relative position of pole and observer at every station. In the field, such effects may be partially avoided by setting up the instrument at two different heights above the ground.

Terrain-effects may be caused by weathering of surface-rocks which were first homogeneously magnetized, by irregular disposition of other magnetic material, by surface-float of igneous rocks, or by outcrops magnetized by lightning. Correction cannot be made for such effects.

If the surface-rocks are homogeneously magnetized, it is possible to calculate terrain-effects by assuming simple geometric shapes of topographic irregularities. For instance, the maximum magnetic anomaly on a hill-station would be [920], where κ is susceptibility

$$\Delta Z = 4\pi\kappa Z_0 \tag{31}$$

The approximate anomaly near the bottom of a vertical wall is

$$\Delta Z = -(\tfrac{4}{3})\pi\kappa Z_0 \tag{32}$$

and the approximate anomaly in the bottom of a V-shaped valley is

$$\Delta Z = -2\pi\kappa Z_0 \text{ (gentle slope) to } -3\pi\kappa Z_0 \text{ (steep slope)} \tag{33}$$

These equations bring out the important fact that valley-stations show negative anomalies if the rocks above are magnetic. In areas of igneous rocks, differences between stations on the summit and in the valley may be between 100 and 1,000 gammas.

(7) NORMAL VALUES

To obtain magnetic anomalies, that is, effects of geologic bodies free from the normal terrestrial field, normal values must be subtracted from observed readings. There is no standard procedure for doing this. Depending on the size of the area surveyed, Governmental maps may be used to obtain the normal value, or this normal value plus a regional anomaly may be subtracted. It is sometimes preferable to determine normal values at the end of a survey from the appearance of the anomaly curves.

V. THEORY OF INTERPRETATION

Magnetic data can be interpreted in terms of surface-geology as soon as the results have been properly plotted in graphical form. Generally, one or all of the three following graphical methods of representation are employed: First, curves of equal anomaly; second, anomaly-profile curves; and third, anomalous vectors as explained below.

Interpretation may be based on these data in two ways. Most magnetic interpretation is qualitative, the fundamental idea being that a positive magnetic anomaly* would indicate a high of a homogeneously magnetized body or else a concentration of magnetic material, and a negative magnetic anomaly would mean the opposite. Qualitative magnetic interpretation can be very successful if it is firmly established that the geologic body in question is normally magnetized. If such is not the case, it is better to abandon the magnetic data altogether and use another geophysical method in which a more consistent physical property can be utilized. Certain cases of qualitative interpretations may be extended into quantitative interpretation when data on the form of the geologic body are available or may be assumed safely. This condition exists for the majority of iron-ore bodies, for tabular magnetic formations and some types of igneous intrusions, and for many cases of homogeneously magnetized basement-rocks.

---

*In the Northern Magnetic Hemisphere.

The simple case of iron-ore bodies may be treated as a single pole or as a magnetized line. Tabular formations are treated as magnetic plates; basement-rock topography may be treated by calculating its gravimetric anomalies as illustrated below.

Most quantitative magnetic interpretation is of an indirect nature. From the shape of the magnetic anomaly, certain assumptions are first made as to possible depths and dimensions of the geologic body or bodies causing the anomaly. Then the effect of such body or bodies is calculated and compared with the field-data. By steps the assumptions about distance and dimensions of the geologic body are changed until an agreement between field-data and theoretical assumptions is obtained.

Where geologic bodies of simple shape and shallow depths are encountered, such as is frequently the case when prospecting for iron-ore bodies, the depths of these bodies may be calculated directly from the shape of the anomaly-curve without resorting to the indirect procedure of interpretation.

Certain types of geologic structures, particularly those with irregular topography, are difficult to calculate. Then model-experiments made with magnetic bodies on a small scale in the laboratory may be used to simulate field-conditions and to arrive at depth-interpretation of the field-data.

Often the distance to geologic bodies may be determined by making observations in two levels of a mine or by flying two profiles in two different altitudes in aerial magnetic surveys.

In the following paragraphs the subject of graphical representation will be treated first. After that the theory of poles and magnetic lines will be given, then the fundamentals on the relationship of magnetic and gravitational anomalies will be outlined and the use of torsion-balance interpretation-diagrams in magnetic interpretation will be illustrated. The Chapter will be concluded with descriptions of model-experiments and underground and aerial magnetic surveys.

(1) Graphical representation

(*a*) *Isanomalic lines*

In northern magnetic latitudes the results of magnetic surveys are best represented by lines of equal anomaly in vertical intensity (or total intensity in superdip surveys, see Fig. 11-*A*). The interval of the contour-lines should be two to three times the middle error of the survey. However, greater intervals have to be used for large magnetic anomalies. Isanomalic maps are comparable with topographic maps and their use will be facilitated by shading areas of equal anomaly.

(b) *Profiles at right-angles to strike*

In such profiles the magnetic anomaly is shown in the form of a curve above the known or assumed geologic section (see Figs. 8 and 10). Generally, vertical-anomaly curves and horizontal-anomaly curves are shown. The vertical-intensity values as obtained in the field may be utilized. However, horizontal-intensity anomalies should be re-calculated in terms of values projected on the direction at right-angles to the strike, particularly where large anomalies of declination have been observed.

(c) *Disturbance-vectors*

These vectors may be shown for the horizontal plane, for the vertical plane, or in three-dimensional form. The horizontal disturbance-vector is tangent to the direction of the projection, on a horizontal plane, of the lines of force radiating from the geologic body (see Fig. 7). Their construction requires a knowledge of normal and actual declination in addition to the normal and anomalous (or actual) horizontal intensity. Actual horizontal intensity is plotted in the direction of actual declination, normal horizontal intensity in the direction of normal declination, and the horizontal disturbance-vector is obtained by vectorial subtraction.

Vertical disturbance-vectors are generally superimposed on a vertical section through the known or assumed geologic section at right-angles to the strike (see Fig. 10). The vertical anomalous vector may be obtained as the resultant of the vertical and horizontal anomalous intensities. When the Hotchkiss superdip is being used, the vertical anomalous vector is obtained by plotting normal total intensity in the direction of normal inclination and subtracting this vector vectorially from the observed total intensity plotted in the direction of observed inclination (see Fig. 9).

Total disturbance-vectors are the resultant of horizontal and vertical disturbance-vectors. The best way of plotting them three-dimensionally is by using isometric projection.

(d) *Magnetic gradients*

These may be plotted by calculating rate of change and direction of change of intensities from magnetic contour-maps, or directly from observations made with magnetic torsion-balances or inductive gradiometers.

(2) POLE- AND LINE-THEORY [921]

Particularly when magnetic ore-deposits are being prospected for, the ore-bodies may be represented by single poles if they have the shape of vertical dikes and extend to such depths that the effect of the lower pole becomes negligible.

Referring to Figure 5, assume that a pole of the strength, m, is located at a distance, r, from the point of observation, P. r may be resolved into the two coordinates, e and d, or into the three rectilinear coordinates, x, y, and d.

As the potential of the pole at P is (m/r), the force in the direction of r is

$$F = dV/dr = -m/r^2$$

and therefore the components in the three directions and the horizontal-intensity anomaly in the direction of e are

$$\begin{aligned} \Delta X &= \partial V/\partial x = -xm/r^3 \\ \Delta Y &= \partial V/\partial y = -ym/r^3 \\ \Delta Z &= -\partial V/\partial d = dm/r^3 \\ \Delta H &= \partial V/\partial e = -em/r^3 \end{aligned} \tag{34}$$

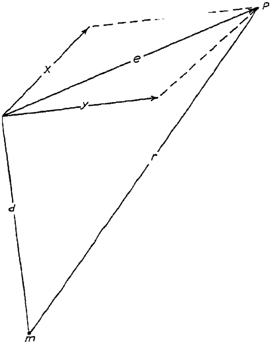


FIG. 5.—Effect of magnetic pole.

It is seen from these equations that the vertical intensity has a maximum when $r = d$, that is, above the pole. It is likewise seen that the horizontal intensity is zero above the pole, has a negative anomaly toward the north where x is positive, and a maximum toward the south where x is negative. The lines of force for a single pole are straight; the isanomalics of vertical intensity are concentric circles. The following interpretative rules follow directly from equation (34). First, the highest point of a polarized subsurface mass lies immediately below the maximum anomaly in vertical intensity and below the zero-point in horizontal intensity. Second, the disturbance-vectors intersect in the pole. Third, the drop of the vertical-intensity curve is inversely proportional to the depth of the pole. Fourth, designating the distance of a point where the maximum vertical-intensity anomaly has dropped to one-half of that value as $e_{\frac{1}{2}}$, the depth of the pole is given by

$$d = (\tfrac{4}{3})e_{\frac{1}{2}} \tag{35}$$

Fifth, the distance of the point where the maximum vertical-intensity anomaly has dropped to one-third of its value is equal to the depth of the pole. Sixth, the distance of a point where vertical-intensity and horizontal-intensity anomalies are equal, that is, where the angle of the disturbance-vectors with the horizon is 45°, is equal to the depth of the pole; the ΔH-curve intersects the ΔZ-curve at the point where $\Delta Z = (\frac{1}{3})\Delta Z_{\max}$.

By arranging a series of poles in a straight line it is possible to calculate the effect of magnetized plates of steep dip. If the surface of such a magnetized plate has a distance, d, from the surface and if the point, P, has the coordinates of x', y', then the relations of equations (36) hold for the vertical- and horizontal-intensity anomalies (see Fig. 6).

$$\left.\begin{aligned}\Delta Z &= 2Cd/e^2\\ \Delta H &= 2Cx'/e^2\end{aligned}\right\} \tag{36}$$

where C is a constant depending on susceptibility, normal vertical intensity, and thickness of plate.

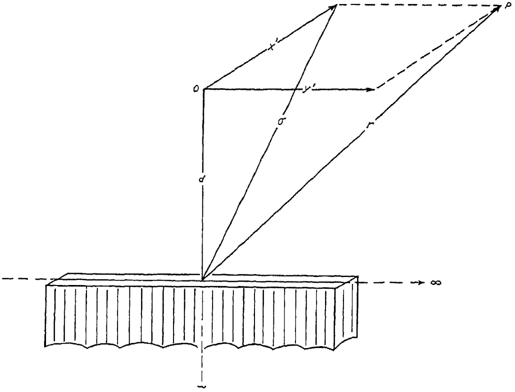


FIG. 6.—Effect of magnetized sheet.

The following depth-rules follow for these relations: (1) The distance between the point where the vertical-intensity anomaly has its maximum from the point where it has dropped to one-half of its value is equal to the depth, that is

$$d = \tag{37}$$

(2) At a point where the vertical- and horizontal-intensity anomalies are equal this distance is equal to the depth—in other words, equality of vertical- and horizontal-intensity anomalies occurs where the vertical intensity has dropped to one-half of its maximum value.

The effect of double poles, or of magnets, has to be substituted in interpretation for the effect of single poles if the depth-extent of the geologic body is small compared with the distance at which the anomalies are measured.

The case of a vertical magnet may be calculated by simple superposition of the effect of two poles, that is, by applying equation (34) twice. Then if d_1 is the depth to the upper pole and d_2 the depth to the lower pole, the horizontal- and vertical-intensity anomalies are

$$\left.\begin{aligned} \Delta H &= em\left[\frac{1}{(e^2 + d_2^2)^{\frac{3}{2}}} - \frac{1}{(e^2 + d_1^2)^{\frac{3}{2}}}\right] \\ \Delta Z &= m\left[\frac{d_1}{(e^2 + d_1^2)^{\frac{3}{2}}} - \frac{d_2}{(e^2 + d_2^2)^{\frac{3}{2}}}\right] \end{aligned}\right\} \qquad (38)$$

The effect of a dipping magnet may be calculated by applying equation (34) twice for different depths and horizontal positions of the upper and lower pole. Then if d_1 is the depth to the upper pole, e_1 the horizontal distance of the point of observation from the upper pole, $2l$ the length of the magnet and i its dip from the horizontal, then the horizontal- and vertical-intensity anomalies are given by equations (39).

$$\left.\begin{aligned} \Delta H &= m\left[\frac{-e_1}{r_1^3} + \frac{e_1 - 2l \cos i}{r_2^3}\right] \\ \Delta Z &= m\frac{d_1}{r_1^3} - \frac{d_1 + 2l \sin i}{r_2^3} \end{aligned}\right\} \qquad (39)$$

For dipping plates, the corresponding formula may be calculated by applying equation (36) twice for an upper and a lower magnetized line in different horizontal and vertical positions. It is also possible to calculate by means of the equations previously given the effects of geologic bodies of any shape or topographic outline by assuming a series of poles or lines and adding their effects.

It is seen that the effects of single poles differ from the effects of magnetic lines by the fact that the former are inversely proportional to the square of the distance, while the latter are inversely proportional to the first power of distance. Nevertheless, practical experience has shown that the values for depth calculated by either method do not show an appreciable difference. At any rate, there is always some uncertainty as to the distance of the pole of an ore-body from its upper surface.

(3) RELATION OF GRAVITATIONAL AND MAGNETIC ANOMALIES

As seen from equations previously given, the pole-theory makes no assumption about the origin or direction of magnetism in a geologic body. On the other hand, it must be expected that the direction of magnetization in a geologic body bears some relation to the direction of the terrestrial field except when the geologic body has very distinct dimensions in one direction.

It is possible to give the theory of the effect of magnetic bodies in a somewhat more quantitative form by considering them to be due to the induction in the Earth's magnetic field, and thereby a relation between strike, dip of the geologic body, and direction and intensity of the Earth's magnetic field may be stated.

In giving the theory for this case, use is made of a relation of gravitational and magnetic potential which is stated by the theorem of Poisson as in equation (40),

$$V = (I/G\sigma)(\partial U/\partial i) \tag{40}$$

in which V is the magnetic potential, I is the intensity of magnetization of the geologic body, σ is the density in contrast to that of the surrounding medium, G is the gravitational constant, U is the gravitational potential, and i is the direction of magnetization. The equation indicates that the magnetic potential is equal to a constant multiplied by the gravity-component in the direction of magnetization.

From equation (40) follows the magnetic force in any direction, s,

$$\partial V/\partial s = (I/G\sigma)(\partial^2 U/\partial i \partial s) \tag{41}$$

which may be written

$$\partial V/\partial s = (1/G\sigma)[(\partial/\partial s)(I\partial U/\partial i)] \tag{42}$$

It is advantageous to separate, for two-dimensional geologic bodies, the intensity of magnetization, I, into the transverse horizontal magnetization, α, and the vertical magnetization, γ, and further to resolve the gravity-component in the direction of magnetization, into the horizontal gravity-component $\partial U/\partial x'$ at right-angles to the strike, and the vertical gravity-component $\partial U/\partial z$. Then equation (42) is written

$$\partial V/\partial s = (1/G\sigma)\{\partial/\partial s[(\partial U/\partial x')\alpha + (\partial U/\partial z)\gamma]\} \tag{43}$$

where x' is the direction at right-angles to the strike.

Applying this to the horizontal and vertical anomalies, we have the relations of equation (34).

$$\left.\begin{aligned} \Delta H &= \partial V/\partial x' = (1/G\sigma)[(\partial^2 U/\partial x_1'^2)\alpha + (\partial^2 U/\partial x'\partial z)\gamma] \\ \Delta Z &= \partial V/\partial z = (1/G\sigma)[(\partial^2 U/\partial x_1'\partial z)\alpha + (\partial^2 U/\partial z^2)\gamma] \end{aligned}\right\} \tag{44}$$

The significance of these two equations is readily seen when applied to extreme cases of latitude or dip. In high magnetic latitudes where the direction of magnetization is nearly vertical, the horizontal-intensity anomaly corresponds to the horizontal gravity-gradient which, as known from torsion-balance work, is zero over the center of gravity of the geologic body and has its maximum and minimum anomalies on the flanks. On the other hand, the vertical-intensity anomaly is proportional to the vertical gravity-gradient which, owing to the theorem of Laplace stated below, is equal to the torsion-balance curvature value for two-dimensional bodies. Therefore, the vertical-intensity anomaly has its maximum over the center of the geologic body.

In equation (44) the transverse horizontal magnetization is

$$\alpha = \kappa H_0 \sin \epsilon$$

where κ is the susceptibility, H_0 is the normal horizontal intensity, and ϵ is the strike of the geologic body from north. Also, γ is equal to $\gamma = \kappa Z_0$ where Z_0 is the normal vertical intensity in the area. Using abbreviations customary in torsion-balance work

$$\partial^2 U/\partial x'\partial z = U_{x'z} \qquad \partial^2 U/\partial x'\partial y' = U_{x'y'}$$

and

$$\partial^2 U/\partial y'\partial z = U_{y'z} \qquad \partial^2 U/\partial y'^2 - \partial^2 U/\partial x'^2 = U_{\Delta'}$$

and applying Laplace's equation $\nabla^2 U = 0$ or

$$\partial^2 U/\partial x'^2 + \partial^2 U/\partial y'^2 + \partial^2 U/\partial z^2 = 0$$

we obtain

$$\begin{aligned} \Delta H &= (1/G\sigma)(-\alpha U_{\Delta'} + \gamma U_{x'z}) \\ \Delta Z &= (1/G\sigma)(\alpha U_{x'z} + \gamma U_{\Delta'}) \end{aligned} \tag{45}$$

or

$$\begin{aligned} \Delta H &= (\kappa/G\sigma)(-H_0 \sin \epsilon U_{\Delta'} + Z_0 U_{x'z}) \\ \Delta Z &= (\kappa/G\sigma)(H_0 \sin \epsilon U_{x'z} + Z_0 U_{\Delta'}) \end{aligned} \tag{46}$$

Torsion-balance gradients and curvature-values have been calculated by various authors for many simple shapes of geologic bodies, and their formulas may be substituted directly into equation (46) to obtain the magnetic horizontal- and vertical-intensity anomalies. In doing so, simplifications may be introduced for extreme conditions, that is, for high magnetic latitudes and for extreme angles of dip. Fairly simple relations may be obtained in this manner; as an example, reference is made here merely to the formula given by Smyth about 40 years ago for a vertical magnetic plate which may be written in simplified notation as in equation (46*a*)

$$\Delta H = 2C \log (r_2/r_1) \qquad \text{and} \qquad \Delta Z = 2C(\varphi_2 - \varphi_1) \tag{46a}$$

where r_2 and r_1 are distances and φ_2 and φ_1 are angles to the edge of the plate. Equation (46*a*) follows directly from equation (46) for the extreme of vertical magnetization and neglect of transverse magnetization.

(4) USE OF TORSION-BALANCE DIAGRAMS IN MAGNETIC INTERPRETATION [915, 916]

Formula (46) may be used to calculate magnetic effects from the corresponding torsion-balance formulas, not only for geometric bodies but also for bodies of irregular outline. For this purpose, torsion-balance interpretation-diagrams are applicable. They consist of so-called graticules showing outlines of mass-elements which increase from the reference-point in such manner that their effect on a torsion-balance set up at the reference-point is equal; hence, to determine the effect of a geologic body of given outline on the torsion-balance at that point, all that has to be done is to superimpose a graticule on the outline and to count the number of elements comprised by the geologic body. For curvatures and gradients, two different kinds of diagrams are employed. If n is the number of elements comprised by the geologic body in the gradient diagram and m is their number in the curvature-diagram, if C is the unit effect of such elements, and σ is the difference in density involved, we have for gradients and curvature-values

$$U_{x'z} = C\sigma n \qquad \text{and} \qquad -U'_{\Delta} = C\sigma m \tag{47}$$

from which follows for the horizontal- and vertical-intensity anomalies

$$\left.\begin{aligned} \Delta H &= \kappa C'(H_0 \sin \epsilon \cdot m + Z_0 \cdot n) \\ \Delta Z &= \kappa C'(H_0 \sin \epsilon \cdot n - Z_0 \cdot m) \end{aligned}\right\} \tag{48}$$

where C' is equal to C/G.

(5) MODEL-EXPERIMENTS

Model-experiments have been applied in magnetic interpretation to simulate the effects of ore-bodies and geologic structure of irregular outline. In mining work, ore-bodies may be simulated with sufficient accuracy by models of tin or iron. These may be left in position and small compasses or dip-needles made specially for this purpose may be moved across them at different vertical distances to simulate depths; or else regular magnetometers may be used, left stationary, and the model ore-bodies may be moved underneath them and in such manner as to simulate depths and horizontal distances to scale.

To simulate the effect of basement-rocks or other geologic bodies of irregular topography, a model may be made of some plastic substance to scale. As suggested by Barrett, this may be energized by a pair of Helmholtz coils oriented at the angle of correct dip and supplied with alternating current. The magnetic instruments at the Earth's surface may be simulated by a smaller coil to pick up either the horizontal or vertical component. The coils are not rotated but the electromotive force picked up by them is rectified and read on a sensitive galvanometer.

(6) UNDERGROUND AND AERIAL MAGNETIC SURVEYS

Underground magnetic surveys are beset with many difficulties on account of interference from power-lines, pipe-lines, and magnetic rocks close to the instrument. Where applicable, however, they will give valuable information on the position of ore-bodies, particularly when enough drifts and stopes are available so that the observer may get the effect of the same body from different levels and directions.

A related application is depth-determination of ore-bodies by making measurements on the surface and also on a platform erected some 10 to 20 feet above. Only depths to upper poles of ore-bodies may be determined in this manner, but not the depth to the lower pole. The same principle is applicable to the determination of depth to basement-rocks in aerial magnetic surveys by recording magnetic effects in two traverses flown at different altitudes.

VI. RESULTS OF MAGNETIC SURVEYS

In the space available for this brief summary it is impossible to discuss even an adequate portion of the many magnetic surveys which have been published in the international literature for the past 20 years. The data from commercial work done in this country alone exceed all published data many times. Discussion of a few typical examples will suffice.

Magnetic prospecting results may be divided into three groups, namely, those obtained (1) in mining exploration, (2) in oil-exploration, and (3) in civil engineering.

(1) Results in mining exploration

Magnetic prospecting in mining has had for its objective (*a*) location of iron ores such as magnetite and hematite, (*b*) location of non-magnetic ores associated with magnetic minerals, (*c*) location of concentrates of noble minerals associated with magnetite, and (*d*) determination of structure of formations in mining areas.

Probably the best-known example of the application of magnetic prospecting to the location of iron-ore is the work done through almost a decade at Kursk where magnetic anomalies exceeding the normal magnitude of the Earth's field components have been observed by Lasareff [461], Gamburzeff, Haalck [916], and Slichter [1417]. Also well known is the application of magnetic methods in prospecting for iron-ore in various districts in Sweden, for which the work at Kirrunavaara by Carlheim-Gyllensköld [451] is an instructive example. In Figure 7, an underground magnetic-vector survey is reproduced conducted in the Kallmerberg Mine in Sweden, after Keilhack ["Lehrbuch der praktischen Geologie," **1,** 381 (1921)].

Many examples have been published on the application of magnetic methods to the location of magnetic and non-magnetic sulphides, and other commercial minerals associated with magnetic formations. A well-known example is the work done on the Falconbridge ore-body by Slichter [1417], by Eve and Keys [910], etc. Figure 8 illustrates magnetic

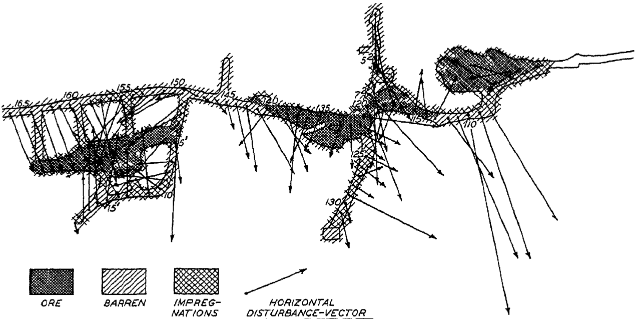


FIG. 7.—Underground magnetic survey of iron-ore body at Kallmerberg, Sweden (*after Keilhack*).

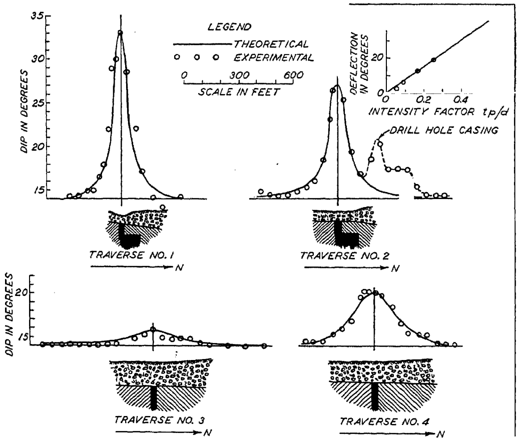


FIG. 8.—Observed and theoretical response of Falconbridge pyrrhotite ore-body (*after Slichter*).

anomalies observed and calculated for this ore-body at various depths and demonstrates clearly the effect of varying depth on the anomaly-curve. Other applications of the magnetic method to the location of commercial ore associated with magnetic formations are: The location of copper in magnetic lava-flows [1420], bauxite in igneous rocks [1420], diamonds in peridotite-plugs [1420], gold-bearing quartz veins in igneous rocks [1411], and ore-accumulations of sulphides on the flanks of highs of igneous rocks [1406]. In Figure 9, the application of the Hotchkiss superdip to the location of a peridotite-plug and depth-determination by the vertical anomalous-vector method is illustrated.

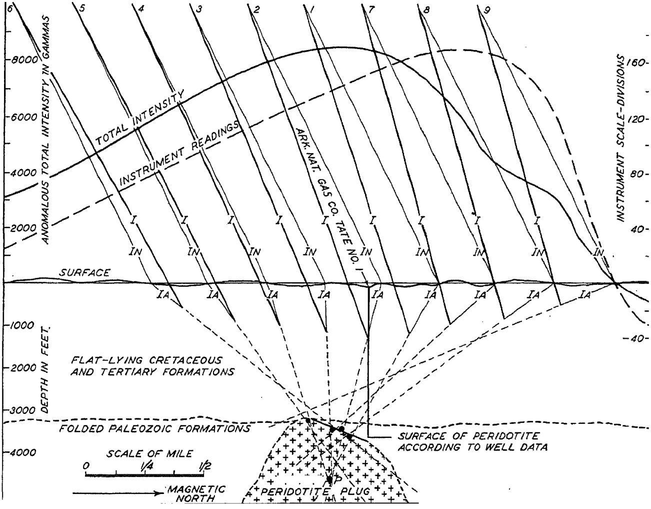

6
5
4
3
2
1
7
8
9
-8000
-6000
-4000
-2000
ANOMALOUS TOTAL INTENSITY IN GAMMAS
TOTAL INTENSITY
INSTRUMENT READINGS
ARK. NAT. GAS CO. TATE NO. 1
INSTRUMENT SCALE-DIVISIONS
160
120
80
40
I
IN
SURFACE
IA
-1000
-2000
-3000
-4000
-40
DEPTH IN FEET
FLAT-LYING CRETACEOUS AND TERTIARY FORMATIONS
FOLDED PALEOZOIC FORMATIONS
SURFACE OF PERIDOTITE ACCORDING TO WELL DATA
SCALE OF MILE
0
1/4
1/2
MAGNETIC NORTH
P
PERIDOTITE PLUG

FIG. 9.—Magnetic vectors and intensity-profile across peridotite-plug near Rison, Arkansas (*after Stearn*): *I* = recorded magnitude and direction; *IN* = normal component; *IA* = anomalous component.

Considerable work had been done with magnetic methods in tracing gold-placer accumulations magnetically. Articles dealing with this subject are comparatively few [1407]. Figure 10 shows two anomaly-curves obtained on the banks of a gold-bearing creek-bed near Golden, Colorado.

The magnetic method also finds considerable application in determining general trends and details of structure in mining districts. Studies of this nature have been made in Canada as described in the papers of Lundberg [1410-*A*], and Eve and Keys [910], etc., and in the copper- and iron-ore districts of Michigan, Minnesota, and Wisconsin [1401, 1420], etc.

(2) RESULTS IN OIL-EXPLORATION

The function of the magnetic method in oil-exploration is to locate highs of buried hills and of anticlines and to map faults, intrusions, and topography of basement-rocks. The work done in this country from 1925 to 1930 by oil-companies far exceeds what has been published on this subject. Probably the most complete and extensive survey published is one of the Arbuckle and Wichita Mountains, extending into other areas of Oklahoma and Texas, presented by Van Weelden [1423]. Other more isolated magnetic surveys for oil-exploration have been described by Stearn [1420]. Figures 11-*A* and 11-*B* illustrate how well, in favorable cases, the correlation between basement-topography, structure in overlying sediments, accumulations of gas and oil, and magnetic anomalies may work out.

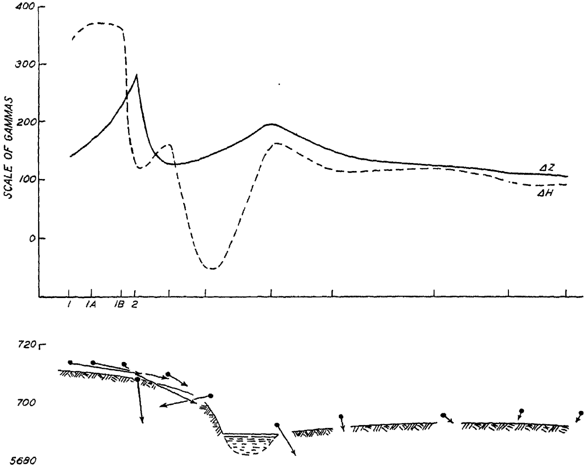


FIG. 10.—Magnetic anomalies on placer-gold deposit near Golden, Colorado.

In northern Europe, the magnetic method has been applied fairly extensively in search for salt-domes; however, this has not proved to be a successful method of locating such domes in the Gulf Coast, Colorado.

(3) RESULTS IN CIVIL ENGINEERING

While the magnetic method—the dip-needle in particular—is applied frequently in construction work to locate pipe-lines and other buried iron

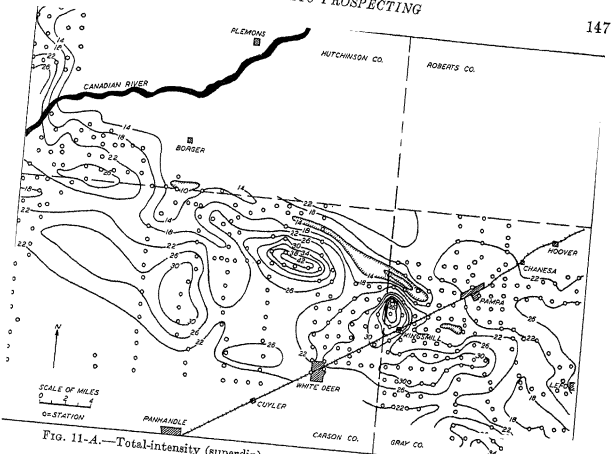


FIG. 11-*A*.—Total-intensity (superdip) anomalies over buried Amarillo Ridge, Texas.

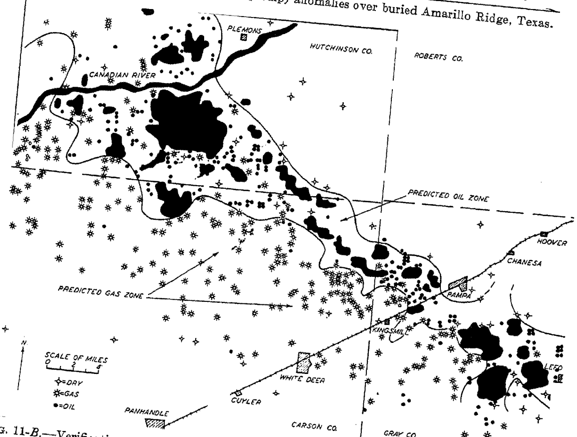


FIG. 11-*B*.—Verification of predicted oil- and gas-areas by later oil- and gas-production (*after Stearn-Kelly*).

objects, systematic surveys of this character have not found their way into the literature. Reference is made to the subject of locating buried ammunition magnetically by Ebert [1404]. Naturally, the magnetic method may find application in locating building material when this is an igneous rock [1416]. Probably one of the most instructive demonstrations of the value of magnetic methods in civil engineering was given recently in the construction of the Bonneville Dam where, in the course of the excavations, basalt-dikes were quite unexpectedly encountered. The magnetometer was then used to outline the dikes, one of which was put to good use as foundation for the power-house.

CHAPTER IV

ATMOSPHERIC ELECTRICITY

O. H. Gish

Department of Terrestrial Magnetism, Carnegie Institution of Washington

An endeavor is made here to outline briefly for the non-specialist the outstanding unsolved problems of atmospheric electricity that engage the attention of the specialist at the present time. Only those aspects of instruments and methods, of facts and theories, that seem needed for background are presented. The references (see Chapter XIII) are necessarily limited and selected with a view to being helpful as a guide either to the more extensive bibliographies or to the more exhaustive discussions in some of the excellent treatises that have been published within the last 15 years.

I. HISTORICAL INTRODUCTION

The first epoch in the development of knowledge about atmospheric electricity may be regarded as beginning in the year 1750. That remarkable Philadelphian quartet, Franklin, Kinnersley, Hopkinson, and Sing, who were first introduced to electrical experiments late in 1746, experimenting during leisure time, had in a few months formed fundamental concepts about electricity which, as formulated by Franklin, became known as the Franklinian theory and were widely accepted. But it is their discovery of "the wonderful effect of pointed bodies both in drawing off and in throwing off the electrical fire" made at this time that concerns us here. Franklin, who credits this observation to Hopkinson, was quick to see in it various implications, one of which was the possibility of protecting buildings, ships, etc., from "the most sudden and terrible mischief" of lightning, by erecting "on the highest parts of those edifices upright rods of iron made sharp as a needle, and gilt to prevent rusting, and from the foot of those rods a wire down the outside of the building into the ground. . . . " His experiments with models had convinced him that if the storm-clouds were charged with electricity, then protection from lightning by utilizing the "power of points" should be effective.

In an elaborate letter (dated July, 1750) to his friend Peter Collinson, a London merchant, amateur botanist, and member of the Royal Society, Franklin ventured to mention the foregoing suggestion, described the experiments which supported it, and outlined the plan of an experiment for determining whether clouds are electrically charged and whether that charge may be drawn off by sharp points as was done in the experiments with models. Collinson was so impressed with the experiments and suggestions contained in this and previous letters from Franklin that he decided to have them published. The first successful performance of Franklin's experiment fell to the lot of Dalibard who erected at Marly la Ville, near Paris, an iron rod one inch in diameter and 40 feet high, insulated from earth and sharply pointed on the upper end. On May 10, 1752, during a thunder-storm a number of intense sparks were drawn from the rod. A few days later Dalibard in a report to the French Academy says, "Franklin's idea ceases to be a conjecture, here it has become a reality." Franklin successfully made his famous experiment with a kite at Philadelphia in June of the same year. He experimented systematically with the electricity drawn from the key near the lower end of the kite-string and found it to have the same properties as that produced by his friction-machine. Soon after this, the first practical application of knowledge of electricity (the lightning-rod) came into use and investigators in all parts of Europe were stimulated to experiment with the electrical phenomena of the atmosphere.

Lemonnier, in France (1752), found that a state of electricity also exists in the atmosphere at times when the sky is clear although with manifestations much less intense than at time of storm. This conclusion was verified by Beccaria in Italy who carried out careful and systematic observations for a period of about 20 years (1757–75) from which he further concluded that the electrical intensity, or field-strength, in the atmosphere during fair weather varies throughout the day in a somewhat regular manner. This diurnal variation was more accurately determined by De Saussure in Switzerland who also reported that the field-strength during fair weather is less and more irregular in summer than in winter.

De Saussure, beginning in 1766, in addition to devising "one of the first, if not the first" electrometer, introduced the "mobile conductor," or electrostatic induction-method, for probing the electrical field (1785). These contributions constituted a great advance over previous methods. The mobile-conductor method consisted of an electrometer with a wire about one-half meter long connecting to the sensitive element. First earthed, then raised quickly a meter or more away from the Earth, the electrometer showed a response which was proportional to the electrical field-strength. The response of the mobile conductor is instantaneous whereas a rod armed with one or more sharp points at the exposed end responds rather slowly in the less intense fields that exist during fair weather. At such times the action of the sharp points depends upon the normal electrical conduction through the air; hence, more time is required for an observation and better insulation must be maintained than when using the mobile conductor.

But the observations with the mobile conductor are of interest for their bearing on the interpretation of the observed facts. Beccaria had made a considerable study of the "power of points" and concluded that, although this property seemed to depend somewhat upon wind-velocity, it ultimately depended upon some special and unaccountable property of air. For a satisfactory understanding of this property, namely, the electrical conductivity of air, it seemed necessary to wait more than 100 years for the discovery of X-rays and radioactivity and the development of the ionic theory of electrical conduction in gases. The action of the mobile conductor, which doubtless seemed more mysterious at the time, was explained much sooner.

Franklin found in 1753 that the electrical charge collected by his sharp points at times of storm was sometimes positive, sometimes negative, but those who investigated the electricity of the air during fair weather always obtained a positive charge. Since the sharp points were commonly supposed to draw off the electrical charge of the air, and since the higher the point the greater the charge that was collected, it was concluded that the air is charged with positive electricity and to a greater extent the greater the altitude. De Saussure, and possibly also Beccaria, took exception to that interpretation for what now seem good reasons, but the other view was championed by the eminent Volta and was generally accepted until about the middle of the nineteenth century. Volta did not use the sharp point as a "collector" but instead utilized an observation made by Franklin in the year of Volta's birth, namely, that flames or incandescent solids have the power of discharging electrified bodies. A small lighted candle or burning fuse was placed at the top of an insulated rod which was set vertically in the electric field and was connected with an electroscope. This type of collector is much more effective than the sharp point for probing electric fields of the relatively low intensities that ordinarily prevail in the atmosphere and is occasionally used at the present time. This device, however, was thought to act by drawing off the electric charge of the air in the manner of the sharp points, which may account for Volta's defense of the erroneous interpretation. Had he experimented with the mobile-conductor method, his views might have been different, for however mysterious the action of that device may have seemed it could not have been regarded as drawing off charge from the air.

Although a sound basis for an understanding of the action of the mobile conductor was not provided until Faraday announced his laws of electrostatic induction a half-century later, yet Paul Erman in Germany, experimenting with De Saussure's method, reached the conclusion (1803) that a negative charge on the Earth could give rise to all the effects that are observed during fair weather. The explanation of the action of the mobile conductor was first given by Peltier in France about 1840, who also added to the reasons and evidence already given by Erman and De Saussure for the dissenting opinion but was unable to shake the complacent acceptance of the older view which continued to be held until about 1860 when William Thomson (later Lord Kelvin) presented his masterful discussion of the problems of atmospheric electricity.

Before the end of the eighteenth century many facts of fundamental importance about the electric field in the atmosphere near the Earth's surface were established. It was found that: (*a*) During fair weather the field was such as to tend to cause positive charges in the air to drift toward the Earth; (*b*) the intensity varied from time to time and from place to place; (*c*) during storms the intensity of the field was much greater than during fair weather and often varied rapidly both in intensity and in direction; and (*d*) the strength of the fair-weather field was greater in winter than in summer. Of course, the conception of an "electric field" was not yet developed nor was it thought that positive electricity in the air does drift toward the Earth.

Observations were extended, somewhat intermittently, during the first half of the nineteenth century and although improvements in both instruments and methods were effected, yet the measurements—fairly precise—were not expressed in a common unit of measure, hence results obtained by one investigator could not be compared with those found by another.

Lord Kelvin's contributions to electrostatics, his comprehensive interpretation of known facts about the electric field of the Earth, his incisive statements of the general problems, his application of the conception of potential and of equipotential surfaces, his development of instruments and methods started a new epoch in the study of atmospheric electricity about the year 1860.

With reference to the electrification of the air, Kelvin pointed out that according to Green's theorems "it is impossible, in the nature of things, to investigate the bodily electrification of a non-conductor by any observation whatsoever of electric action without it" and that therefore "the balloon must be put in requisition if knowledge of the distribution of electricity through the atmosphere is to be sought for." However, even though a thorough investigation of the electrification of the air cannot be made without leaving the Earth, yet, as Kelvin states, "we can make important inferences about it from observations of electric density over the Earth's surface" and he urged "incessant recording" and a sort of "electrogeodesy." He contributed to the first by inaugurating at the Kew Observatory near London the first continuous registration of air-potential and to the second by making measurements with portable apparatus at a number of places on the Earth.

In order that his measurements at different places should be comparable, he expressed the deflections of his electrometer in terms of the number of Daniell cells required to give the same deflection as that observed when the electrometer was connected with the collector which acquired the potential of the air at a certain point. He also took precautions to avoid any distortion of the field by the presence of the observer and the instruments; he selected sites for the observations which were as free as possible from the distorting effects of buildings, trees, and other protruding structures; and finally he took into account the height from the ground of the collecting point. In this way absolute measurements of the electric field-strength near the Earth's surface were realized for the first time.

About 16 years after Kelvin had published his important contributions to the subject, physicists, perhaps stimulated by resolutions presented by Kelvin and Rowland at the International Electrical Congress in 1883, manifested an awakened interest in the electrical phenomena of the Earth and the atmosphere. Continuous registration of air-potential was begun at a number of widely distributed places, some observations were made at sea, on the Indian Ocean, in both the north and the south polar regions, and during the last decade of the century a few successful attempts were made in Austria, France, and Germany to explore the electric field of the atmosphere with the aid of balloons. The electric potential of the air during fair weather was found to be positive with respect to the Earth at such widely distributed places that this seemed to be a world-wide characteristic. The strength of the electric field near the surface was generally found to be greater in winter than in summer and a regular variation during the day was observed at all places although the character of this varied in a puzzling manner from place to place. The observations in balloons showed a decrease of the potential-gradient with altitude. This was the first definite evidence that the net electric charge of air in the first few kilometers from the Earth is generally positive. It had finally become recognized that during fair weather a negative charge resides on the surface of the Earth and that the lines of force extending outward from the Earth end on positive charges located either in the atmosphere or possibly in remote space. The exploration with balloons had indicated that the complementary positive charge is, at least in part, located in the lower regions of the atmosphere. But these positive charges in the air were commonly regarded as being comparatively stationary relative to the Earth. Prominent consideration was not given to the possibility that these charges may drift along the lines of force until they unite with the negative charges on the Earth and that the electric field may thus eventually be destroyed unless there is some provision in nature by which the negative charge of the Earth and the positive charge of the atmosphere are continuously replenished.

That the air is not a perfect insulator and that electric charge may be dissipated through it was recognized by Coulomb, who in 1785, after experimenting with charged bodies exposed in air, concluded that the charge diminishes in geometrical progression as the time increases in arithmetical progression. This conclusion was verified by others and has come to be known as Coulomb's Law which may be stated in simpler form as follows: A charged body completely exposed in air, at a given instant, loses charge at a rate that is proportional to the total charge on the body at that instant, or in mathematical form $dQ/dt = -aQ$, where Q represents the quantity of charge, t is time, and a is known as the coefficient of dissipation.

This discovery of Coulomb, however, received little attention until Linss in 1887 reported his determinations of the dissipation-coefficient, made twice each day at Darmstadt, Germany, during two years. The values varied from a maximum in summer to a minimum in winter and, as was pointed out later by Elster and Geitel, the monthly means increased or decreased when those for the electric field-intensity decreased or increased, respectively. Then in the last decade of the century Elster and Geitel perfected the method of measuring electrical dissipation from charged bodies and made numerous measurements in the outside air, from which they concluded that the dissipation of charge is greatest in pure air and that fog, smoke, or other factors which reduce the visibility, also reduce the dissipation, sometimes to values as low as one-tenth that for very clear weather. Although it was theretofore believed that the moisture in the air helped to discharge a body, yet Elster and Geitel concluded that in pure air the dissipation decreases when the air becomes nearly saturated with water-vapor. They found, as was already indicated by their observations in the lowlands, that in the pure air of the mountains electrical charges are dissipated more rapidly than elsewhere. But their observations on mountains disclosed another interesting part of this picture puzzle. Although in the lowlands electricity was dissipated from a charged body exposed in the outside air at about the same rate whether the charge was positive or negative, yet it was found that on exposed mountain peaks during clear weather a negative charge was dissipated much more rapidly than one of positive sign.

Thus it became evident that the air of the atmosphere has the property of conducting electricity to a very slight yet a sufficient degree for this property to play an important rôle in the electrical phenomena of the atmosphere. It was the conception of ions in gases developed at this time, chiefly by J. J. Thomson and his collaborators, which enabled Elster and Geitel to fit these interesting facts of observation into a general picture. The introduction of that conception opened the modern epoch in atmospheric electricity.

II. GENERAL SURVEY

In its simplest form an ion consists of a molecule of air that has either one more or one less than the quota of electrons for the electrically neutral molecule. The former is a negatively charged, the latter a positively charged ion. Positive ions are attracted toward negatively charged bodies while negative ions drift away from them toward positively charged bodies, and when an ion reaches a charged body its charge goes to neutralize part of that of the body. This process goes on and the body loses its electrical charge at a rate that is proportional to the abundance of ions and to the velocity at which they move toward the attracting body. That velocity is less if the ion is not of the simple type just described but consists of an aggregate of many molecules such as a water-droplet, or a particle of dust or smoke, provided the charge is the same as that of the simpler ion. It is now established that many ions undergo a transformation from the small to the large type, and thus become quite sluggish, when the air is laden with fog, dust, smoke, etc. As a result, electricity is dissipated through such air less rapidly than through pure air in which the ions are largely of the smaller and more mobile type.

According to the ionic theory, the explanation of the observation that on mountain peaks a negatively charged body loses its charge much faster than does one that is charged positively is as follows: The surface of the Earth is charged negatively during fair weather and that surface-charge is greatest on protruding portions such as mountain peaks; hence, negative ions drift away from the Earth while positive ions in the air above drift toward it. Negative ions are therefore somewhat less abundant near the Earth's surface, especially over mountain peaks, than are ions of positive sign although at distances farther from the Earth ions of each sign are about equally abundant. Thus in air near the Earth's surface, the number of negative ions available being less, a body charged with positive electricity loses that charge more slowly than does one that is negatively charged. Although Elster and Geitel observed this only on mountain peaks, a similar difference has since been found to occur quite generally near the surface though it is less prominent over level areas and for such field-strengths as prevail during fair weather.

Wherever fair weather prevails, positive ions are nearly always drifting to the Earth at an average rate of about 2,000,000 each sec on each square foot of surface, or over 2,000 per cm^2 each sec, thereby tending to neutralize the negative charge of the Earth. Yet the charge of the Earth though it waxes and wanes—in part rhythmically, in part irregularly—is in the long run undiminished. How is the negative charge of the Earth maintained? How are negative ions supplied to the Earth, or positive ions removed from the high atmosphere, at an average rate of 2,000 per cm^2 each sec? What are the source and nature of this "supply-current" which has thus far evaded all attempts to detect and measure it directly? Does it have its origin in the Earth, in the atmosphere, or in more remote space? These questions cannot be definitely answered, for they pose the most outstanding unsolved problem in atmospheric electricity, a problem that has baffled investigators for at least 40 years and has led some to venture the surmise that the solution may have to await the discovery of a new physical principle or unsuspected property of matter.

Although the supply-current has not been detected directly, its average magnitude and something about the manner in which it varies may be inferred from measurements of the current that normally flows from air to Earth. The density of this air-earth current may arise in part from processes other than electrical conduction, or the drift of ions in the electric field. Dust, rain, or snow falling to the Earth carries charges, sometimes of one sign, sometimes of the other. It is estimated from measurements of the charge on precipitation that in areas of storm the transport of charge by this process is frequently much greater than the normal electric conduction-current in those areas, but since only a relatively small part of the Earth is covered by storms at a given instant the total "precipitation-current" for the whole Earth is doubtless small compared with the total conduction-current. According to the greatest estimate, that made by Wigand, it is about 20 per cent of the conduction-current. Observations indicate that the net "precipitation-current" like the usual conduction-current is directed toward the Earth, a fact which contradicts a view, suggested by Gerdien, namely, that the charge carried to the Earth by precipitation constitutes the supply-current.

Wind also transports electricity when the air contains more ions, or other charged particles, of one sign than of the other. Although the electricity transported by straight horizontal winds doubtless often corresponds to a current of greater intensity than the air-earth conduction-current, yet no charge is carried toward or away from the Earth by that means. It is only the vertical component of the wind which can do that. But since as much air goes up as comes down, in the long run for the Earth as a whole, the net electrical current along the vertical from this source would be zero except for the circumstances which are described in the following paragraph.

The mixing action of wind as manifested in the lateral scattering of smoke, dust, etc., is a familiar phenomenon. Dust is removed from the Earth and diffused to considerable heights in the atmosphere by horizontal winds. Electricity is doubtless also transported vertically in the atmosphere by this process of diffusion because the air near the surface is generally deficient in negative ions. The mixing, or diffusion, effected by the wind tends to counteract this deficiency, thus in effect returning some of the negative ions to the lower levels from which they were removed by the electric field. This diffusion-current may be regarded as an electric current which flows in a direction opposite to that of the electric conduction-current, the latter, in the conventional sense, flowing toward the Earth while the former flows away from it. The circumstances which favor the existence of a diffusion-current that is consistently directed away from the Earth apparently exist most of the time and nearly everywhere on the Earth. As a result, the net electric current that flows in the air toward the Earth may, in the average, be less than the conduction-current by the amount of the diffusion-current when, as is usual practice, the conduction-current is measured at a position one or more meters from the surface. Estimates of the average magnitude of the diffusion-current differ rather widely but it seems very unlikely that it exceeds 25 or 30 per cent of the conduction-current at levels in the air where the latter is usually measured and it is probably much less at most places. Immediately at the surface of the Earth this mechanism for transporting charge can scarcely be effective at all.

These mechanical processes of transporting charge toward or away from the Earth during fair weather seem therefore to be of secondary importance if estimates based upon facts thus far available are to be relied upon. They nevertheless have bearing on the study of the fundamental problem since such processes modify the distribution of ions in the atmosphere and thereby affect the electric field and the electrical conductivity. Sometimes this occurs in such a manner as to alter indirectly the air-earth conduction-current even during fair weather. However, wind and gravity doubtless play more than secondary rôles in the development of the electrical disturbances which are often so conspicuous during storms, but it is chiefly within the clouds that these forces are thought to act in that capacity. [For further discussion of electrical phenomena of thunder-storms, see Chapter XII.]

Thus it seems likely that electrical conduction has a dominant rôle in the transport of electricity to or from the Earth and that observations of the electric conduction-current may accordingly be expected to give considerable information about the magnitude and character of the supply-current, showing whether it varies during the day and during the year, whether it increases or decreases from year to year, and if so in what manner—whether regularly or irregularly. Those features of the air-earth conduction-current, which may be identified as characteristics of the supply-current, can then be studied in relation to other phenomena in an endeavor to locate the source of that current and to form a conception of the mechanism which maintains it. These remarks indicate the part that the measurement and study of the air-earth conduction-current are expected to play in attempts to find the solution of the basic riddle presented by the phenomena of atmospheric electricity.

However, the air-earth conduction-current and the elements upon which it immediately depends, namely, the electrical field-strength and the electrical conductivity of air, are influenced by various factors, other than the supply-current, which affect the number, the mobility, and the distribution of ions. These influences vary so much from time to time and from place to place that, in order to identify features derived from the supply-current, it is necessary either to measure the air-earth current simultaneously at a sufficient number of places on the Earth and for sufficiently long periods of time so that the average may be a representative sample for the Earth as a whole, or else measurements of the various influencing factors must be made simultaneously with those of the air-earth current so that, after due allowance is made for the effect of these factors, the observations at a more limited number of places may provide a more representative sample.

This simple statement is designed to indicate the elaborate program of observations required in order to arrive at more definite conclusions regarding characteristics of the supply-current, but that program is far more comprehensive than any that has thus far been realized anywhere on the Earth, although most of the various aspects have been carried out here and there and now and then by various investigators working independently. In that way the preliminary development of methods and equipment needed for such a program has been furthered. Unless, and until, the means are found for carrying out a more complete and better coordinated program of atmospheric-electric observations, conclusions and generalizations regarding some features of apparent importance can only be presumptive.

The foregoing remark applies with especial force to electrical transport in storm-areas, even as to the gross aspects, for although some evidence is at hand which suggests that the net current from air to Earth in such areas may be directed oppositely to that in fair-weather areas and that in the total for the whole Earth the air-earth current in storm-areas may balance that over the rest of the Earth, yet this can at present be regarded only as an acceptable possibility that should be tested. However, the difficulties which stand in the way of making the measurements required to determine definitely whether the supply-current is generated in the thunder-storm or other electrical storm are so great that in testing this interesting possibility a study of the limited number of more direct observations must be supplemented by less direct methods of investigation such as the study of the air-earth current in the fair-weather areas.

The air-earth current may be measured either directly, by collecting the current on an insulated plate mounted flush with the surface, or indirectly by measuring the air-conductivity, λ, and the electric field-strength, E, at a point in the air. In the latter case the current-density, i, is obtained from the relation $i = \lambda E$. It is this indirect method which has been the most extensively used. Both E and λ may be registered continuously with automatic apparatus. Registrations of E have been made at a considerable number of places and for a long period of years in a few cases but the registration of λ, which requires more elaborate equipment, has been done at only a few places, while simultaneous and complete registration of both λ and E, suitable for yielding a continuous record of i, has been effected at less than half a dozen places on the Earth.

Such determinations of i, together with numerous values obtained by manual observations at many places on the Earth, notably those observed at sea during the cruises of the yacht *Carnegie*, show the following general characteristics with a varying measure of definiteness: (*a*) The conduction-current in fair weather is directed toward the Earth, that is, positive ions move toward and negative ions away from the Earth in all areas where fair weather prevails; (*b*) it varies somewhat less from time to time and from place to place than does either of its component elements λ and E; (*c*) it undergoes, nevertheless, considerable variation from place to place over land, but apparently not at sea—thus the value measured at the Kew Observatory near London is only one-fifth that observed on the oceans; (*d*) it is apparently greater at places on land well above sea-level than at places in the lowlands; (*e*) although λ increases and E decreases with altitude in the free atmosphere, yet i is about the same at all levels at a given time and over a given place on the Earth; (*f*) it varies with a yearly period at most places over land but this period varies in character from place to place to such an extent that the maximum may be found in summer at one place and in winter at another; (*g*) it varies with a daily period similar to that in the field-strength, with a maximum value at the same time (four to eight hours before Greenwich midnight) everywhere on the Earth—there are relatively few exceptions and these may be accounted for by local circumstances.

Which of these features of the electrical conduction-current are derived directly from the supply-current, and thus reveal something about the characteristics of the latter, and which arise from subsidiary influences that introduce aspects unrelated to the supply-current? Out of these questions others arise such as: What subsidiary factors bring about changes in air-conductivity and in field-strength, and under what circumstances do these produce local and temporal changes in the air-earth current? These lead to inquiries regarding factors that determine the density of the ion-population, the birth-rate and the death-rate of ions, their mobility and migration, and the distribution of ion-populations in all three dimensions of the atmosphere.

It is toward finding answers to such questions as these that investigations in atmospheric electricity are primarily directed. However, the several phenomena which play subsidiary rôles in the fundamental problem of atmospheric electricity are of interest in themselves, and as natural phenomena deserve study, not only for what may thereby be directly added to general knowledge, but also for what such studies may contribute toward the solution of problems in other branches of science—particularly geophysics—and to supply information that is needed from time to time in dealing with matters of more immediate and practical concern. Some of these more specific problems are outlined in the latter part of this Chapter.

Some examples of relations between atmospheric electricity and other branches of science will be mentioned here in order to counteract any tendency to regard this subject as one apart from others—a tendency that might arise from the fact that some of the most important contributions from atmospheric electricity to other subjects have been negations, a type of contribution that is not always popular.

If a telegraph-line extending up a mountain side is connected to earth at two different levels, electric current generally flows in the line from the lower toward the higher point. Considerable evidence of that character has led to the conclusion that electric current flows in the Earth from the base toward the summit on all sides of a mountain. It is sometimes implied that at the summit the current completes its course through the atmosphere. However, the current indicated by these observations is more than 10,000 times the intensity of the vertical conduction-current that is usually measured in the air over mountains. With the restrictions thus placed upon the interpretation of these observations, an interesting problem emerges which may be discussed together with another which arises from the following circumstances.

When measurements of the Earth's magnetic field are used to evaluate the magnetic line-integral around any chosen area on the Earth's surface, the result generally differs from zero. This, according to a fundamental principle of electromagnetism, is to be taken as evidence that an electric current flows vertically across the area. The current which is indicated in this way flows downward out of the atmosphere into the Earth in some considerable areas and upward in others. The average current-density is about 10,000 times that of the air-earth current that is derived from atmospheric-electric measurements so that it seems inadmissible to interpret either this aspect of the Earth's magnetism or the currents observed in telegraph-lines on mountain slopes as manifestations of vertical electrical currents in the atmosphere unless there is involved here some principle or some mode of electrical transport that is as yet unknown to physics. Thus these several classes of data together define a problem that may be of fundamental importance to physical science.

Because of the importance of the cosmic radiation as an ion-forming agency in the troposphere and lower stratosphere, indicated long ago, measurements of that radiation have often been made as part of a program of atmospheric-electric investigations. Some of the decisive evidence that this radiation is not of terrestrial origin was obtained in this way. For example, measurements made daily at sea during cruises of the yacht *Carnegie* showed the presence over all oceans of a penetrating radiation of approximately constant intensity at the surface. At the same time measurements of the radioactive content of sea-water and of the air over the oceans showed that this penetrating radiation could not be attributed to any known source in the Earth. This and other lines of evidence, particularly the measurements made in manned balloons, first by Hess and later by Kolhörster, convincingly indicated that this penetrating radiation is of extra-terrestrial origin.

That the air over land contains radioactive matter, that this matter comes from the Earth along with the air exhaled from the soil, and in greater quantity with the gases that issue from many hot springs and from volcanoes, and that nearly all types of rocks and soil contain measurable amounts of radioactive matter, was first found in the course of the search for the agents that produce ions in the atmosphere. This discovery, that radium and other radioactive substances occur widely distributed in the Earth, has turned out to be important to geology, since this radioactive matter, although a very minute constituent, influences the thermal state of the Earth and also serves as a clock from which the age of formations may be estimated. [See "Age of the Earth," Nation. Res. Council, Bull. No. 80; also "Radioactivity," Nation. Res. Council, Bull. No. 51.]

The auroras, or polar lights [see Chapters X, XI, and XII], are thought to be brought about by the movement of electric charges in the high atmosphere so that one might expect to observe some electrical manifestations near the surface of the Earth when auroras are in evidence. Although the magnetic field and electric currents in the Earth are disturbed at such times [see Chapters I, VII, and VIII], yet no prominent changes in the electric field of the atmosphere near the Earth appear to be associated with them. This definitely restricts the manner in which the auroras are to be explained. Some possible minor relations that have been reported by a few observers require further investigation.

Radio waves are known to be reflected from the high atmosphere [see Chapters IX and X] at altitudes of about 100 km and upward, a circumstance which makes long-distance radio-communication possible. A satisfactory explanation of this is that the concentration of ions at the level where reflection occurs has a certain specified value, which is much greater than at lower levels. Reflections of short waves are also reported by some investigators to have been received from much lower levels, even as low as one km. That the latter type of reflections cannot be brought about by the state of ionization at levels below 22 km seems to be indisputably attested by measurements obtained in the course of investigations of atmospheric electricity. This is another of the negations offered by observations of atmospheric electricity, one which cannot be disregarded in the further study of this curious phenomenon of radio.

Many relations between meteorology and the electrical phenomena of the atmosphere are observed. It was thought long ago that information regarding the electrical state of the atmosphere should assist in forecasting weather, but such expectations have not been realized in any important manner. A study of these relations has thus far revealed no definite evidence that the electrical state influences any phenomena of weather but, instead, the reverse relation is generally found. This is to be expected since it is now known that the energy involved in the electrical phenomena of the atmosphere is exceedingly small in comparison with that represented by the various meteorological phenomena.

It is well known that the intense electrical disturbances which often accompany storms are matters of great practical concern. The static that is so annoying in radio reception is one of the less noxious ways in which these interfere with human affairs. On every hand consideration must be given to protection from the destructive effects of lightning. Provisions for this purpose vary in complexity from the simple lightning-rod of Franklin to the elaborate protective devices required on lines used in the transmission of electric power. Even during fair weather the electric state of the atmosphere may be in some circumstances a source of hazard encountered by hydrogen-filled balloons. The engineering practice in these matters may perhaps be made yet more effective when atmospheric electricity, especially the stormy aspect, becomes more thoroughly understood.

Does the electrical state of the atmosphere have any bearing on human health or is it a factor in determining that feeling of well-being which often comes and goes in an unaccountable manner? This question has been repeatedly raised by physicians, physiologists, students of public health, and more recently by air-conditioning engineers. Some first steps have been taken toward finding the answer to this question by F. Dessauer and associates at Frankfurt am Main, Germany, A. L. Tchijevsky and associates at Moscow, U.S.S.R., C. P. Yaglou at Harvard University, Cambridge, Massachusetts, and by a few other investigators. The group at Frankfurt reports evidence that negative ions in concentrations of 10,000,000 per cc when inhaled with air for 15 to 30 minutes two or three times per week have beneficial effects and that positive ions have detrimental physiological effects in man. The Russian group reports similar results in their experiments with fowls. Yaglou, however, found no evidence for concluding that the ions in the air give rise to any definite physiological effect. The normal concentration of ions in the atmosphere is so much less than that used in these experiments—generally less than one ten-thousandth that used by Dessauer—that even if the report of positive results mentioned above should later be verified it would not yet follow that the ions in the atmosphere play a rôle in human health. Furthermore, when one considers the extreme minuteness of the ion-concentration near the Earth, which is about 1 ion to 10,000 million-million air-molecules, it appears that to attribute any appreciable physiological effect to them would necessarily imply that they have an extraordinary potency in a rôle analogous to that of a catalyst or enzyme.

This may be emphasized by giving the total mass of all the ions which are estimated to enter the lungs of an individual in one year through the process of respiration. It is the small amount of one mg or the equivalent in weight of a drop of water about one mm in diameter or the size of the average drop that falls during moderate rain. The total energy given up in a year by these ions in going from the ionic state to the neutral state, which they must do shortly after entering the lungs, is doubtless less than 300 ergs or less than the energy required to lift a weight of one mg three meters against gravity. Another interesting observation [689] that deserves attention in this connection is that ions are exhaled in respiration at from 50 to 100 times the rate at which they are inhaled. Such are some of the considerations that may be based on facts gathered during the investigation of aspects of atmospheric electricity, which, if they do not suggest a definite answer to the question posed above, should at least assist toward making a correct appraisal and interpretation of the results of experiments that are specifically directed toward finding the answer.

Most of these examples illustrate how the data of atmospheric electricity establish boundaries which limit the range of speculation about some other phenomena and thereby assist in making more precise interpretations of them.

From this general survey it will be seen that many investigations in atmospheric electricity are directed toward finding the mechanism by which negative electricity is supplied to, or positive electricity removed from, the Earth at a rate sufficient to maintain the negative charge on the Earth and to balance the electric current which results from the drifting of negative charge away from, and of positive charge toward, the Earth during fair weather. Those investigations are guided by the expectation that if the current which results from the drifting of charge is completely determined for the whole Earth, then the magnitude of the unknown source, which shall here be designated the supply-current, its distribution over the Earth, and the manner in which it varies with time, may thereby be determined. This information should then provide clues regarding the mechanism which generates the supply-current.

Although it is not feasible to carry out this ideal program, an approach toward it may eventually be realized. That seems to be the only general method of attack now in view. Because greater difficulties attend investigations during storm than during fair weather, the latter have been the more extensive and approach closer to the ideal requirement. Features of the supply-current that are indicated principally by observations of the electrical state of the atmosphere during fair weather are outlined more specifically in the latter part of this Chapter.

III. ELECTRICAL CONDUCTIVITY OF THE ATMOSPHERE

The interchange of electricity between the Earth and the atmosphere during fair weather is doubtless effected chiefly by electrical conduction, as has already been indicated in the general review. An ion, when in an electrical field of unit-strength, attains a certain definite average velocity, k, which is termed the mobility of the ion. When the field-strength is one volt/cm, that velocity is about 1.4 cm/sec for the positive ion and somewhat more for the negative ion of the class (small ions) which plays the dominant rôle in electrical conduction. In a field of strength, E, the velocity with which an ion moves is kE and if the ion carries with it a charge, e, the motion of this charge is equivalent to an electric current, ekE. If there are n ions in each cc the current across each cm^2 would be $nekE$. Generally there are both positive and negative ions present in the atmosphere, and since the negative ions move in a direction opposite to that for the positive ions, they contribute an added amount to the current. Thus, if there are n_1 positive ions/cc and n_2 negative ions/cc, the current which flows perpendicularly through a cm^2 of surface, that is, the current-density, i, is given by $i = e(n_1k_1 + n_2k_2)E$. When conditions are such that the current is proportional to the field-strength—this is usually the case in the atmosphere during fair weather—then this expression is analogous to Ohm's Law and $e(n_1k_1 + n_2k_2)$ corresponds to the electrical conductivity or its reciprocal corresponds to the resistivity. The former term is generally used in discussions of atmospheric electricity. It is represented in this discussion by the symbol, λ. From the form of the expression it is seen that one part is contributed by positive ions, the other by negative ions. These components are represented by λ_1 and λ_2 and are designated positive conductivity and negative conductivity, respectively. Should the air also contain other types of ions having different mobilities, the expressions for each of the components of conductivity would contain a sum of terms like nk. Fortunately, although several types of ions are present in the atmosphere, the term for the small, or more mobile, type of ions apparently predominates except under circumstances which are relatively rare, namely, when the air contains an abundance of certain types of pollution. Since it is well established that the charge on each small ion is not variable and is one electronic charge, or 4.77×10^{-10} ESU, it follows that the conductivity is determined by the density of the small-ion population, or briefly the ionic density or ionic concentration, and by the mobility of these ions.

(1) MOBILITY OF IONS

Many determinations of the mobility of small ions in pure dry air have been made in the laboratory by a variety of methods which are described in treatises on the conduction of electricity through gases [1299, 1300, 1302]. The values for the mobility of the positive ion assembled by the Thomsons average 1.37 cm^2/volt/cm and those for the negative ion average 1.91 cm^2/volt/sec. Some authorities seem to prefer a somewhat lower value for the negative ions. Thus Loeb in the first edition of "Kinetic theory of gases" (1927) uses for k_1 1.4 and for k_2 1.8 cm^2/volt/sec; however, in the later edition (1934) he gives $k_1 = 1.6$ and $k_2 = 2.2$ cm^2/volt/sec. The mobility of ions in air is quite accurately proportional to the reciprocal of the air-density for the range of density that must be considered here. Zeleny [1306] first noticed that the mobility of the negative ion is decreased when the amount of water-vapor in the air is increased, whereas that of the positive ion was unaffected. Several other observers have found a similar effect. Thus Griffiths and Awberry [1291] report that the mobility of the negative ion decreases 18 per cent as the relative humidity increases from 0 to 100 per cent. The variation of mobility with relative humidity will accordingly result in only minor variations—less than nine per cent—in air-conductivity at sea-level which can be left out of account in most considerations. The dependence of mobility upon density, although a minor factor at sea-level, is a major factor in the increase of conductivity with altitude. Values of mobility determined from observations of conductivity and ionic density over the oceans indicate a dependence upon latitude, the mean for the latitude-belt 20° north to 20° south being about 20 per cent greater than that for the belt 40° to 60°, north or south. This is of the right character but too great to be wholly attributed to the difference in air-density.

The mobility is very dependent upon the nature of the ion. The mobility of the electron, which is much greater than that of the small ion, although dependent upon the ratio of field-strength to pressure, has, for usual conditions near the Earth's surface, a value probably not greater than 20,000 cm^2/volt/sec [1284]. However, despite this large mobility, electrons remain free so short a time and are so scarce that the contribution to the conductivity of air is negligible in the troposphere and lower stratosphere.

The small ion in the air of the lower atmosphere immediately when formed doubtless consists of a single molecule but this simple state lasts only a fraction of a second when other molecules become associated with the simple ion. According to Loeb [1296], one, two, or perhaps three molecules may be added. Some of the small ions, however, become attached to particles of dust or other aggregates of molecules, thus forming much larger and less mobile ions. The fact that the mobility of the positive ion is less than that of the negative ion has been attributed to the attachment of more, or other types of, molecules to the initial positive ion. Thus Erikson [1289] concludes from his experiments that the initial positive ion in air has a special affinity for molecules of water-vapor and that for air which is completely free from water-vapor and other impurities the mobility of the positive ion would be the same as that of the negative ion.

That the addition of an extremely minute quantity of some substances to a gas may result in large changes in the mobility of ions is shown by various investigations, notably those of Loeb and his students. This seems to result from a special affinity between the ions and the molecules of these impurities. Several investigators are of the opinion that some such impurities are produced in the process of ionization. It is likely that ions of a class first found in the atmosphere by Pollock [668], and which shall be called intermediate ions, are in part formed by the attachment of small ions to molecules, or molecular complexes, of such impurities. These intermediate ions have a mobility of from one-tenth to one one-hundredth that for the small ions [1304, where it is stated that at zero mm vapor-pressure the mobility of the intermediate ion is 0.5 cm^2/volt/sec and at 30 mm vapor-pressure it is about 0.05 cm^2/volt/sec].

That ions having a mobility about one five-thousandth that of the small ions are present in the atmosphere was first established by Langevin [1295]. These Langevin or large ions although submicroscopic have a mass more than a million times that of a molecule of air [658]. They apparently carry a single electronic charge [657, 664, 1293 (exception); 1299 estimates, p. 404, that in order to take on more than one electronic charge the radius must exceed 4×10^{-6} cm] which is doubtless received largely from small ions. Because of their very small mobility the large ions contribute very little to electrical conduction. The contribution in cases where the large ions are extremely plentiful may amount to a few per cent. Intermediate ions, however, sometimes contribute an appreciable part. At Washington, D. C., this amounts to 15 per cent in the average according to the observations of Wait and Torreson [690].

Direct observations of ions of intermediate mobility have been made at too few places to determine definitely whether such ions are widely distributed in the atmosphere or even to permit generalizations in some other respects. Thus several investigators [Booij, 625; Israël and Schulz, 648; and Weiss and Steinmaurer, 692] seem to find intermediate ions having a wide range of mobilities extending more or less continuously to values near that of small ions, whereas Pollock, Wait, and others find no evidence of an appreciable number of ions with mobilities between that for small ions and about 0.1 cm^2/volt/sec. Schachl [670] found, in the mountains about Innsbruck, Germany, fewer intermediate ions than in the city.

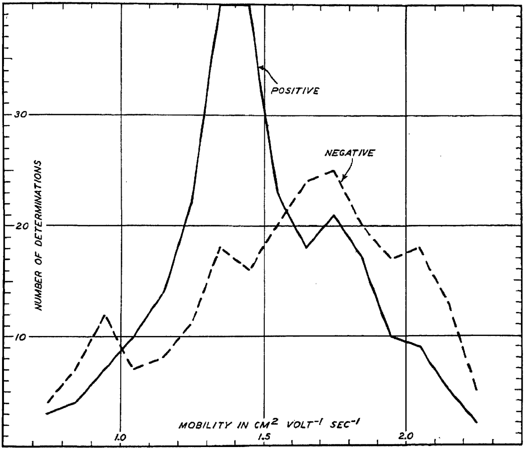


FIG. 1.—Frequency-distribution of determinations of mobility, College-Fairbanks (Alaska) Polar-Year Station, November, 1932, to August, 1933.

That intermediate ions are not plentiful enough to contribute much directly to the conductivity of air at sea and over some land-areas is indicated by indirect determinations of mobility from measures of ionic density and conductivity. Although the value of mobility determined in this way from the relation $k_1 = \lambda_1/(en_1)$ or $k_2 = \lambda_2/(en_2)$ is not very precise, yet when many determinations are considered statistically some significant features are revealed. Data obtained at College-Fairbanks, Alaska [549], and shown in Figure 1 will serve to illustrate this. Mobility is there plotted as abscissa and the number of times a given value of mobility was determined is plotted as ordinate. The mobility of the positive ion, most frequently observed, was 1.4 cm^2/volt/sec and that for negative ions was 1.75 cm^2/volt/sec. Since these values are close to the mobilities found from measurements made in the laboratory and the curves have nearly the character of the normal error curve, it may be concluded that ions having mobilities much less than that of the normal small ions were too scarce at that place to play an important rôle in electrical conduction. The measurements made at sea during the cruises of the *Carnegie* give similar indications. Although this is a feature which deserves more extensive observation, there is in the evidence cited some justification for regarding electrical conduction in the greater part of the atmosphere near the Earth's surface as chiefly dependent upon the number of small ions. The factors which determine the density of the small-ion population therefore require attention in order better to understand aspects of electrical conduction in the atmosphere.

Just as the density of human population in a given region depends upon the birth-rate, the death-rate, and the rate of migration, so also the ionic density depends upon the rate of formation, the rate of destruction, and the migration of ions.

(2) IONIZERS OF THE ATMOSPHERE

Small positive ions are formed when an electron is removed from a neutral molecule. The electron which is set free in this process of ionization may recombine with a positive ion, thus restoring a molecule to the neutral state, or it may become attached to a neutral molecule and form a negative small ion. The latter process preponderates except at very great altitudes where the electronic density is great and the density of neutral molecules very small. Although there are many known agencies which can separate an electron from the neutral molecule, yet only a few of these are generally effective in the atmosphere. The cosmic radiation is the predominant ionizer in the lower stratosphere and in the troposphere except in the lower kilometer or so over land. There the radiations from the radioactive matter in the Earth and in the atmosphere are generally dominant in the formation of ions. In the high atmosphere, from altitudes of about 80 km and upward ultraviolet light from the Sun is doubtless the chief ionizer. When the electric field is very intense (about 30,000 volts/cm at 760 mm pressure) ions may acquire sufficient velocity during the interval between collisions with molecules that their kinetic energy at the time of the next collision is great enough to eject an electron from the neutral molecule. In the rapid repetition of this process many ions are formed. Since this so-called ionization by collision occurs only in the vicinity of storms there is little occasion to consider it in this section. In some special circumstance ions may be formed when light, even of visible wave-length, strikes certain photosensitive substances. However, substances of the required sensitivity are so small a part of the constituents of the Earth that this is doubtless an insignificant ionizer in the atmosphere. Ultraviolet light of sufficiently short wave-length directly to ionize air is apparently all absorbed high in the atmosphere.

Some chemical and a few mechanical processes introduce ions or charged particles into the atmosphere. Large and intermediate ions are doubtless at times introduced into the atmosphere by such means. Studies of the ions in flames [1299, pp. 367–370] show that many flames contain ions of subnormal mobility. These seem to start as small ions which later become attached to liquid or solid products of combustion or other nuclei and rapidly increase in size as they move away from the flame. Domestic and industrial furnaces, bush and forest fires, etc., doubtless play a rôle similar to that of the flame, introducing into the atmosphere some intermediate ions and considerable numbers of large ions, as well as numerous nuclei which serve for the later formation of large ions. These classes of ions are also formed during corona-, spark-, or arc-discharge through gases under conditions in the laboratory. That electrical discharges in the atmosphere may give rise to intermediate ions is consistent with observations of an increased number of such ions during storm [1304].

Small and large ions are reported to be formed when a surface of water is suddenly disrupted. Thus a drop of water when impinging upon a rigid body breaks up into numerous small droplets and several larger ones. In pure water the small droplets carry a negative charge into the surrounding air whereas the larger ones with a positive charge settle to Earth. If the water contains small amounts of certain impurities, the sign of the charges may be reversed. A considerable charge on the fine spray and the air in the immediate vicinity of waterfalls is maintained by this mechanism. On that account it is sometimes called the "waterfall effect." It was first investigated in the laboratory by P. Lenard [716] and is also referred to as the "Lenard effect."

The air along the sea-shore when "breakers" are prominent may receive intermediate and large ions through this mechanism. It is sometimes suggested that this may also take place to a degree when whitecaps are formed at sea; however, the measurements made at sea on cruises of the *Carnegie* give no definite indication of ions contributed in that way. Whether this effect is of primary or secondary importance in the separation of charge in the thunder-cloud is not yet definitely known, but investigations of the last decade generally indicate the latter.

Ions are also said to be formed by drifting dust or snow [614, 1301]. It is certain that charged particles are introduced into the atmosphere at such times since abnormally intense electric fields become manifest in limited areas and for short periods, but in these cases a considerable portion of the particles are doubtless microscopic in size and carry a number of elementary charges. Such entities are usually not placed in the category of ions. Although further investigation is required to ascertain whether and to what extent ions are directly formed by this process, yet indirect evidence indicates that this is generally quite negligible.

Of these several possible means by which ions may be formed in the atmosphere, only two, namely, the cosmic radiation and the radiation from radioactive matter in the Earth and atmosphere, are known to be sufficiently widespread and effective to be dominant factors in the ionization of the atmosphere during fair weather.

(3) Radioactive matter in the Earth and atmosphere

The radioactive matter in the air consists of decay-products of radium and thorium which have come from their mother substances in the Earth. Nearly all constituents of the lithosphere contain uranium and thorium [1219, Chapter VII; 1222, Chapter VII] together with the several decay-products of these elements. In the average, igneous rocks have about twice the radioactive content of sedimentary rocks and, of the former, acidic rocks contain more than basic rocks, the amounts of radium ranging from 3×10^{-12} to 1×10^{-12} gram of radium per gram of rock. In the sedimentaries the radium-content ranges from 1.5×10^{-12} gram/gram for shales to 0.9×10^{-12} for chalks according to a summary [1222, p. 549] attributed to A. Holmes. A puzzling fact is presented by the large radium content found in samples obtained from the ocean-bottom. Those obtained on cruise VII of the *Carnegie* [1223] contain an average of 6.5×10^{-12} gram of radium/gram. Taking into account the relative abundance of the different rock types in the lithosphere J. Joly estimates an average for the whole Earth of 2.0×10^{-12} to 2.6×10^{-12} gram radium per gram of rock, which is equivalent to an amount of uranium of 6×10^{-6} to 8×10^{-6} gram/gram. The radio of the thorium-content to the uranium-content is found to be nearly constant and equal to about 2.2.

The average radium-content of sea-water is apparently much less than that of rocks. Although there is a considerable range in the measured values, Hess takes an average of 2×10^{-15} gram of radium/cc. The content is greater near the coast and the mouths of rivers, whereas no radioactivity could be detected by Hewlett [1214] in samples collected well at sea on cruises of the *Carnegie*, which implies a radium-content of less than 1×10^{-15} gram/cc.

Since the radioactivity in the Earth varies from place to place, one may expect to find somewhat corresponding variations in the rate of ion-formation. There are, however, factors which modify that correspondence. The more effective ionizing rays—the alpha and beta rays—from this radioactive matter are absorbed by a relatively thin layer of earth; hence it is chiefly the more penetrating gamma-rays which reach the atmosphere and produce ions there. The average rate of ion-formation by these alone is estimated by Hess [633] to be three ion-pairs/cc/sec, or about one-third of his estimate for the total rate of ionization. The rest is ascribed to radioactive matter distributed in the air and to cosmic radiation.

The radioactive matter in the air is exhaled from the Earth at a rate which depends upon the abundance of the mother substance in the soil, upon the nature of the soil—for example, its porosity—and upon various other factors which promote or retard the exhalation of gases from the Earth. Thus when the soil is saturated with water, is frozen, or is covered with snow, it gives off radioactive matter to the air at a slower rate than when in a more open and exposed condition. Wind, changes of barometric pressure, and changes in the temperature of the soil doubtless also affect the discharge of radioactive gases from the soil.

That the air contains radioactive matter was first shown by Elster and Geitel [1288]. After some preliminary developments these investigators collected such matter upon a wire some tens of meters in length, which was stretched horizontally in the air and maintained at a negative potential of about 2,000 volts. Radioactive particles, most of which have a positive electric charge, are attracted and become attached to a wire thus exposed. Immediately after the exposure, the wire is coiled and placed in a closed vessel. The increased rate of ionization in the vessel gives a measure of the amount of radioactive matter collected and the manner in which this rate decreases with time indicates the nature of the radioactive matter. Various improvements of this scheme were later employed by other investigators. Radioactive matter is also collected from the atmosphere by passing air through activated charcoal or through other absorbing substances. The radioactive matter thus concentrated is then driven into an ionization-chamber and the quantity and character determined from the magnitude of the ionization and the rate of decay.

It is found that the radioactive matter in the air consists chiefly of radium emanation (radon) and thorium emanation (thoron) and the products which result from the disintegration of these. In order to express the measure of this mixture quantitatively it is referred to the amount of radon which is in equilibrium with one gram of radium. That unit is called the Curie. The amount of radioactive matter in the air near sea-level found from such measurements ranges from about 60×10^{-18} to 400×10^{-18} Curie/cc. Hess takes as a probable representative average 130×10^{-18} Curie/cc for observations over land. The extensive observations made on cruises of the *Carnegie* [608, 1221] show that at sea the amount is much less than over land, the mean of all observations being

2.6×10^{-18} Curie/cc while that of measurements unaffected by large land-areas is 1.2×10^{-18} Curie/cc. The low value at sea is consistent with the scarcity of radioactive matter in the sea-water far from land. Thus while the radioactive matter in the soil, and that which has escaped into the atmosphere, are a large factor in the ionization of the lower atmosphere over land, yet at sea the radioactive matter both in sea-water and in the air, except in so far as the latter is carried to sea from land by winds or the former by streams of water, is too small to play an important rôle in the ionization of air at sea.

Because of the limited life of the radioactive matter the amount in the air will be less the greater the distance from the source. The decrease with distance of course depends also upon the velocity of the wind or upon the activity of other disseminating processes. The distribution of a radioactive element with altitude in the free atmosphere depends upon the mean life of that element and upon the magnitude of (*a*) vertical air-movements, (*b*) the mixing processes (eddy-diffusion), and (*c*) processes, such as precipitation, which remove such substances.

Estimates of the manner in which the radioactive elements should be distributed with altitude by eddy-diffusion have been made by Hess, by Schmidt, and by Priebsch [1224]. From these it appears that for an average state of mixing, or eddy-diffusion (coefficient of eddy-diffusion 22.5 gram/cm^2/sec at 100 meters), the radon-content at an altitude of one km is about 18 per cent of that at the surface; at ten meters the thoron-content is less than one per cent of the surface-value, and the thorium-B content decreases to about four per cent in one km. Measurements made in airplanes by Wigand and Wenk [1229] of the radon-content of air indicates a somewhat more rapid decrease than that given by these estimates. From this and other indirect evidence it appears that there is insufficient radioactive matter in the air at levels of several km over land and in most of the atmosphere over the oceans to be an important factor in ionization there.

C. T. R. Wilson was the first to show that freshly fallen rain or snow contains radioactive matter. This was verified by a number of investigators in the following years. Rain and snow therefore appear to remove radioactive matter from the air and to concentrate it near the Earth's surface. Nearly all the early investigators found that this concentration is more pronounced in thunder-storms than in general rain. While in more recent observations at Innsbruck, Germany, Priebsch [1225] found no such contrast, yet Wait and McNish [782], using a very thin-walled ionization-chamber at Washington, D. C., and Doan [1152], employing a thick-walled chamber at Chicago, found enhanced ionization during thunder-storms. Precipitation, together with the air-circulation of storms, therefore doubtless affects the distribution of radioactive matter both laterally and vertically in the atmosphere. Such factors bring about complex changes from time to time in the ionization of the air over land-areas. However on the open sea, with the comparative scarcity there of radioactive matter, the ionization is relatively unaffected by such processes.

Although there can scarcely be any doubt that numerous variations in the rate of ion-formation over land may be attributed to the changes in the radioactive matter in the air, yet attempts quantitatively to relate cause and effect in these variations encounter numerous difficulties. Thus, for example, if radon issues from the soil in a periodic manner, the ionization in the atmosphere may be expected to manifest a variation of corresponding period, but the amplitude of the latter may be considerably less than that of the former and the variations may be quite out of phase. The disparity in each of these aspects depends upon the relation of the period of the variation to the mean life of radon [1222, p. 589]. When the period is 24 hours, the ionization would lag about six hours.

(4) THE COSMIC RADIATION

The discovery of cosmic radiation, like many discoveries, came about gradually. Investigations by Elster and Geitel, C. T. R. Wilson, Rutherford and Cook, McLennan and Burton, Gockel, and others finally led up to the decisive observations made by Hess (1911) during ten flights in balloons. These showed for the first time that the ionization in a closed vessel first decreases slightly with altitude up to a height of about one km in the free atmosphere, then increases up to an altitude of at least five km (the highest altitude reached in those flights) where the ionization is two to three times as great as at the surface. Observations made by W. Kolhörster (1913) up to an altitude of nine km with improved apparatus verified the observations of Hess up to five km and showed a large additional increase from that level up to nine km. These and all later observations support the conclusion reached by Hess, namely, "that there must exist a very penetrating radiation of extra-terrestrial origin which enters the atmosphere from above, and even at the Earth's surface is responsible for part of the ionization observed in the vessel." The scientific literature on cosmic radiation has been so well reviewed by a number of writers that it seems sufficient to refer to a recent paper by A. H. Compton [1142], which will guide the reader to the original sources.

The intensity of cosmic radiation at sea-level is nearly the same everywhere on the Earth. The chief departure from uniformity consists in a variation with magnetic latitude, the values along the magnetic equator being from about 13 to 20 per cent less than those at magnetic latitudes greater than 50°. The smaller of equatorial values are near longitude 100° east. At sea-level near the magnetic equator this radiation produces between 1.4 and 1.5 ion-pairs/cc/sec at standard temperature and pressure, while in the vicinity of magnetic latitude 50°, 1.70 ion-pairs/cc/sec are produced according to the data accumulated by Compton.

Measurements obtained in recent years with instruments, which were carried far into the stratosphere by manned or by sounding balloons, show that the cosmic-ray intensity continues to increase with altitude until a maximum production of about 300 ion-pairs/cc/sec, at standard temperature and pressure, is reached at the comparatively high altitude of about 24 km, in middle latitudes, after which a decrease sets in which continues to the highest altitude thus far reached. The altitude at which the decrease begins seems to be somewhat less at low than at high latitudes. More pronounced however is the considerably smaller increase of intensity with altitude in low latitudes. Figure 2 illustrates this but it is to be noted that the data plotted are for the rate of ionization at actual, not standard. temperature and pressure.

The variations in the intensity of cosmic radiation during the day, from season to season, or from year to year are apparently too small to be appreciable in other aspects of atmospheric electricity.

(5) RATE OF IONIZATION

The average rate of production, q, of ions near the Earth's surface over land by each of the respective ionizing rays, as calculated by Hess [633, pp. 167–171] on the basis of the average amount of radioactive matter in the Earth and in the air, is as in Table 1. The symbol, I, is used hereafter to denote ion-pairs/cc/sec or ions/cc/sec when there is no chance of ambiguity.

TABLE 1.—*Production of ions near Earth's surface over land in ion-pairs/cc/sec*

Ionizer	Ionizing rays			Total
	α	β	γ	
Radioactive matter:				
In Earth	0	0.1	3.0	3.1
In air	4.6	0.2	0.15	4.9
Cosmic radiation	...	...	....	1.5
Total	....	....	....	9.5

The rate of ion-formation registered at Washington, D. C., in a closed vessel with very thin walls, after appropriate corrections are applied, indicates that the average, q, for conditions there is six to eight I, according to unpublished results of Wait and Torreson. Hogg [641, 642] in 1935 reported that he found by an involved method an average of 20I at Canberra, Australia, although in an earlier report (1934) he gave a much lower estimate. Indirect estimates of q may be made from the concentration of small ions and large ions, or nuclei, provided the constants in the relations between these elements are adequately determined. The determination of these constants, however, generally rests on a direct determination of q. Since the latter is difficult, the values of the constants usually employed may be considerably in error and some of the unexpected results of indirect estimates may be attributed to that and to false preconceptions as to what may be a reasonable value of q. It seems highly desirable that more attention be given to reliable methods for determining this fundamental element, q, directly. However, some information about the variations in q can doubtless be obtained from indirect estimates.

Estimates of q from measurements of the ionization in closed vessels with comparatively thick walls (often one mm or more of steel or other metal) cannot be very reliable where radioactive matter is present in the air, because it is usually not possible with the information at hand to evaluate the corrections which doubtless must be applied, especially when comparing measurements made with different vessels. However, such measurements have been made much more extensively than any other type on which estimates of q may be based.

From these several types of estimates it seems admissible to conclude that over land q varies considerably from place to place and from time to time. A seasonal variation seems to be indicated at several places and a regular diurnal variation is reported for Washington, D. C. [685], Canberra, Australia [641, 642], and Glencree, Ireland [660, pp. 11–59]. Although there seems to be no alternative to the view that the major part of such variations in q over land is a result of variations in the radioactive content of the air, yet it is desirable that this be verified by simultaneous observations of q and of the several factors upon which it depends.

Several investigators attach some significance to the observation that the maximum in the diurnal variation of q occurs at the same universal (Greenwich) time at the three widely separated places mentioned above. If this is eventually verified, it would imply that ionization arises in part from some factor which has not yet been detected. This would constitute a riddle of prime importance. Bongards [1207, pp. 295–296] earlier called attention to indications of a similar universal variation in the radioactive content of the air and suggested that radioactive matter comes into the atmosphere from outside space. Mauchly [608, p. 421], however, pointed out that the very small concentration of radon observed in the air at sea during cruises of the *Carnegie* refutes that suggestion. Variations in q, having a universal character, are also apparently refuted by the numerous observations of the ionization in closed vessels made over the sea and at high altitudes in the atmosphere over land. These measurements show no variations of either the character or magnitude that would be expected if the suggested universal variation in radioactive content or in q were real.

The average rate at which ions are formed at sea-level over the open oceans is doubtless not more than $2I$ and is probably greater than $1.5I$, according to the rate of ionization in a closed vessel measured on cruises of the *Carnegie*. Somewhat lower values are indicated by the measurements of the cosmic-radiation intensity reported by Compton. Allowing for the dependence of q upon air-density the average may be about $1.67I$ at a magnetic latitude somewhat greater than 50° and should not be more than $1.27I$ near the magnetic equator. This apparent dependence of q upon latitude would lead one to expect a corresponding dependence in the ionic density, n. However, on account of the smaller air-density at the lower latitude it is estimated that the average n at the equator does not differ more than ten per cent from that at about latitude 50° where q differs 30 per cent. No diurnal, seasonal, or other periodic variation of q at sea, of sufficient magnitude to require consideration here, has been established by observation. A detectable seasonal change arising from variation in air-density may occur in a few areas where the seasonal range of temperature is relatively large. In general, however, the rate of ionization at sea apparently undergoes no important temporal change. This apparently is one reason why atmospheric-electric phenomena are simpler at sea than on land.

The variation of q with altitude in the free atmosphere depends upon the corresponding variation in (*a*) the intensity, I^0, of the ionizing agent and (*b*) the density, δ, of the air, in accordance with the relation, $q = I^0\delta$, where I^0, the measure of the intensity of the ionizer, is expressed in terms of the number of ions formed by it per cc per sec at standard air-density. The vertical distribution of density in the troposphere and lower stratosphere is known for typical circumstances. The distribution of I^0 in most of that portion of the atmosphere is fairly well known if, as seems reasonably certain, measures of the cosmic-radiation intensity are a close approximation to I^0 everywhere except in a lower stratum over or near continental areas which—as previously mentioned—contains radioactive matter.

Considerable support for calculating q at various levels from observations of cosmic radiation is provided by measurements obtained by E. Regener [1191, pp. 779–784] and associates using an ionization-chamber of unusually large volume with walls of aluminum only 0.2 mm thick and which, instead of being sealed, communicated with the outside air through a small filter. The measurements of ionization in this "open chamber" when reduced to values for constant gas-density agree closely at all altitudes with measurements made with a small closed chamber having thick walls and containing argon under pressure. Further support is given by a comparison of air-conductivity measurements made on the flight of the stratosphere balloon *Explorer II* with values calculated from the measured values of cosmic-radiation intensity (see Fig. 9). That comparison shows that the cosmic radiation alone is a quite adequate ionizer and furthermore, since it is the only one known to be present in the portion of the atmosphere specified above, estimates of q, based on measures of that radiation, are thought to be reliable.

Values of q, for the troposphere and stratosphere, derived in this way from measures of the cosmic radiation reported by Bowen, Millikan, and Neher [1136 and revised values supplied by Professor Millikan in June 1938], for a low and a middle latitude position, are shown in Figure 2.

At both latitudes q increases from the surface upward until a maximum is reached at an altitude of about 13 km where a decrease sets in which continues up to the highest altitudes at which measurements have been made, and doubtless considerably beyond. The decrease of q with altitude sets in at a level six or eight km lower than that where a similar decrease of the cosmic radiation begins, because of the decrease of air-density. The conspicuous difference in the vertical distribution of q at the two different latitudes is largely a reflection of a similar difference in the cosmic radiation. The maximum value of q at the higher latitude is about two and one-quarter times the value for a corresponding level at the lower latitude and at the 20-km level that ratio is nearly three and one-half. This difference in the vertical distribution of q at different

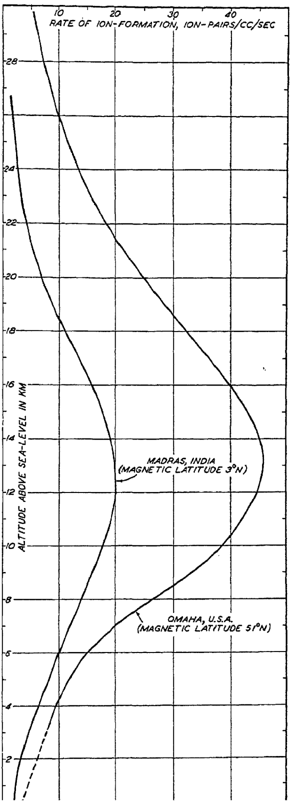


FIG. 2.—Ionization by cosmic radiation in troposphere and stratosphere for middle and low latitudes (*derived from data of Bowen, Millikan, and Neher*).

latitudes implies a corresponding difference for ionic density and for conductivity and should be manifest in some atmospheric-electric features at the Earth's surface.

(6) DESTRUCTION AND TRANSFORMATION OF IONS

The ion-population in a given space increases or decreases until there is a balance between the rate of formation, the rate of destruction, and the rate of migration. Two small ions are destroyed when a positive small ion combines with a negative small ion. The rate at which this takes place is proportional to the product of the concentrations of these ionic species. Thus, if in each cc there are n_1 positive small ions and n_2 negative small ions, the rate at which ions of each sign are destroyed in this way is $\alpha n_1 n_2$ per cc per sec, where α, the coefficient of recombination, has the magnitude, 1.6×10^{-6}, at normal temperature and pressure. When small ions disappear in no other way, such as transformation or migration, and appear only in pairs at a rate q per cc per sec, then the rate of change (dn/dt) in the concentration of small ions of either sign is expressed by $dn/dt = q - \alpha n_1 n_2$. From this one sees that when a balance between the ion-forming and ion-destroying processes is attained, that is, when $dn/dt = 0$, and when $n_1 = n_2 = n$, $n = \sqrt{q/\alpha}$. This simple relation between the ionic density and the rate of small-ion formation is generally regarded as an adequate approximation for the circumstances that prevail in the atmosphere at altitudes of one km and upward, although it is quite inadequate for conditions near the Earth. However, since this relation does not entirely reconcile observations of conductivity and ionic density in some parts of the troposphere and stratosphere with measurements of cosmic radiation in those regions [631, 632], the circumstances there may be such as to require the consideration of other factors.

It was early suspected, and is now well established, that in the lower atmosphere small ions are destroyed in other ways than by combination between oppositely charged ions of that class. The first quantitative investigations of the rôle played by large ions and condensation-nuclei in the destruction or transformation of small ions were made by E. Schweidler [1300, pp. 35–43], by J. J. Nolan and associates, Enright, Boylan, and de Sachy, and by A. D. Power. The considerations are as follows: A small ion and a large ion are destroyed when a small ion combines with a large ion of opposite sign. The rate at which positive small ions of concentration n_1 per cc combine with negative large ions of concentration N_2 per cc is $\eta_{12} n_1 N_2$ per cc per sec. Positive small ions are also transformed into large ions by attachment to neutral nuclei of concentration N_0 per cc at a rate $\eta_{10} n_1 N_0$. In an analogous manner negative small ions combine with positive large ions and attach to neutral nuclei at the rates, $\eta_{21} n_2 N_1$ and $\eta_{20} n_2 N_0$, respectively. The combination coefficients, η_{12} and η_{21}, and the attachment coefficients, η_{10} and η_{20}, are of the same order of magnitude as α.

Large ions of opposite sign are also considered to combine at a rate $\gamma N_1 N_2$. Intermediate ions and uncharged intermediate nuclei, if there are any of the latter, may be expected to act in the destruction or transformation of small ions in a manner similar to that indicated for large ions. The rate of destruction and of transformation of small ions in that way may be expressed by $\mu_{12} n_1 m_2$ and $\mu_{10} n_1 m_0$, respectively, where m_2 is the ionic density or concentration for intermediate ions, m_0 is a corresponding concentration for intermediate nuclei, μ_{12} is the coefficient of combination of positive small ions with negative intermediate ions, and μ_{10} is the coefficient of attachment of positive small ions with uncharged intermediate nuclei. Thus far there has been very little investigation of the part intermediate ions and possible nuclei of corresponding size play in this rôle [641, pp. 1–55]. Wait [1304], however, estimated that the magnitude of, say (μ_{12}/μ_{10}) is quite large and that the coefficient of combination between intermediate ions of opposite sign is 0.7×10^{-6}.

There are reasons for thinking that the coefficients of η_{10}, η_{20}, η_{12}, and η_{21} vary from place to place and from time to time perhaps as a result of change in the character of the nuclei—such as a change in size due to capture or loss of water-molecules. The values in Table 2 indicate the possible range in these coefficients, in units of 10^{-6}.

TABLE 2.—*Range of η in units of 10^{-6}*

η_{10}	η_{20}	η_{12}	η_{21}	Authority
6.8	7.6	8.7	9.7	J. J. Nolan and G. P. de Sachy [665]
0.58	1.07	2.35	2.96	F. J. Scrase [677]

Kennedy [649] finds $\gamma \doteqdot 10^{-9}$; Hogg [641, pp. 1–55] estimated a value nearly 100 times this. Investigations by Wait [685] and several comparisons by Gish, as in Figure 4, indicate values of the η's definitely less than the larger, but somewhat greater than the smaller, of those listed in Table 2.

In a specific case where $n_1 = n_2 = 170$, $N_2 = 2{,}600$, $N_1 = 3{,}000$, $N_0 = 15{,}300$, it follows that $\gamma N_1 N_2 = 0.008I$, $\alpha n_1 n_2 = 0.05I$, while $\eta_{12} n_1 N_2 = 1.0$ or $3.8I$ and $\eta_{10} n_1 N_0 = 1.5$ or $17.7I$. The first of the alternative values is obtained by using coefficients given by Scrase, the second by using those of Nolan and de Sachy.

In this case, although the large ions and nuclei are only moderately numerous, small ions are destroyed almost entirely by combination with large ions or attachment to nuclei. The destruction of small ions due to the combination of small positive with small negative ions and the destruction of large ions by combination of large ions of opposite sign can therefore be neglected when the concentration of large ions is suitable in comparison with that for small ions.

The coefficients doubtless all vary with temperature and pressure but it is thought that at sea-level the variations in the concentration of ions, directly attributable to that source, while not negligible in all considerations, are usually of minor importance. However, this dependence on temperature and pressure, especially the latter, is of major importance for the vertical distribution of small ions. No adequate experimental investigation of the dependence of the η's upon temperature and pressure has yet been made and the conclusions reached by theoretical considerations [693, 1292] are somewhat vague and discordant. Further investigation of this matter is therefore needed.

The dependence of α upon temperature and pressure has been investigated, both theoretically and experimentally (see treatises on conduction of electricity in gases). Thomson states that if "the complexity of the ion remains unchanged" at low pressures α is proportional to T^{-3} and at high pressures α is proportional to $T^{-\frac{3}{2}}$. At a pressure of about one atmosphere, which is between the limits to which the foregoing statement applies, experiment indicates that, for the range of temperature found in the atmosphere, the exponent of T is -2.5 (Erickson) to -2.2 (Phillips). These results are in fair agreement.

The several investigations of the dependence of α upon pressure, however, are not in good accord. According to the usual interpretation of Thomson's theory of recombination, α varies directly as the pressure, p. However, diverse results have been obtained from investigations in the laboratory. These may be described by saying that α varies approximately as p^x where $0 \leqq x \leqq 1$. A comparison of values of air-conductivity, measured on the flight of the stratosphere balloon *Explorer II*, with values of cosmic-radiation intensity, for corresponding altitudes, indicated that x is about one-third. The most recent investigation, by Gardner in Loeb's laboratory [1290], also indicates that α varies approximately as $p^{\frac{1}{3}}$ for ions in oxygen in the pressure-range 30 to 760 mm. It is desirable that these recent results be checked by further investigations, because if α varies, as say the one-third instead of the first power of p, this is a matter of vital importance to theories of the several phenomena which depend upon intense ionization in the high atmosphere.

(7) MIGRATION OF IONS

The population-density or concentration of any species of ions or of nuclei will tend to increase in a given region when the rate of immigration exceeds that of emigration, and the inverse is also obvious. A considerable migration of ions is of course effected by wind. If the wind-velocity is v, the ionic density n, then the flux of ions across a cm^2 of area perpendicular to the direction of the wind is nv. When v and n are constant along the path of the wind, immigration and emigration are equal and there is no tendency of the wind to change the ionic density. However if either n or v or their product varies along the path, then the wind exerts a tendency to increase the ionic density at a given position when the product nv decreases in the direction toward which the wind blows, whereas an increase of nv in that same sense and direction would tend to decrease the ionic density. The same is true for nuclei. Effects of this sort are especially likely to be important in the vicinity of cities or other places where considerable pollution is introduced into the air. The nuclei generally associated with air-polluting substances act greatly to deplete the ionic density of small ions and to increase that of large ions in the city. The transition from this state in the city to that in the less impure air of the country round about doubtless is often sufficiently abrupt to make the change of nv with distance from the center of pollution great enough to be an important factor in determining the small-ion concentration.

Ionic density may also be increased or decreased by the mixing action of wind, or eddy-diffusion. The net effect of the mixing process is to move ions from regions of higher to regions of lower concentration. The rate at which this takes place depends upon the magnitude of eddy-diffusion (expressed by the coefficient of eddy-diffusion, A) and upon the divergence of the ionic density. For example, if the ionic density, n, is less near the Earth than at higher levels, the divergence may be expressed as the negative rate of change of n with altitude, z, or as $-dn/dz$. Then the average rate at which ions are moved across a cm^2 of horizontal surface by this process is $-A(dn/dz)$. This may be regarded as a current of ions flowing toward the Earth, when, as was here assumed, dn/dz is positive. If this current of ions increases with distance from the Earth, it follows that ions enter the upper face of a centimeter cube faster than they flow out at the bottom. Hence in these circumstances eddy-diffusion supplies ions to the air near the Earth at a rate given by $d(A dn/dz)/dz$.

The magnitude of the rate of supply of ions by this means has not been determined but it is doubtless quite appreciable in the case of negative ions near the Earth's surface under average conditions when the potential-gradient is positive.

The migration of ions which results from their drift in the electric field results in a depletion of the number of negative ions near the Earth when the gradient, E, is positive, that is, when the potential of the Earth is less than that of points in the atmosphere. The flux-density of ions of one sign drifting in the electric field is knE, where k is the mobility. If this "current" of ions becomes greater as the distance, z, from the

Earth increases, and if the flow is upward, as it should be for negative ions, then more ions flow out the top than enter the bottom of a unit-cube, so that the ions in that space tend to be depleted by this circumstance at a rate given by $d(knE)/dz$. The depletion of negative ions near the Earth's surface by this means is doubtless appreciably offset by eddy-diffusion. The net effect is that the ionic density of negative ions averages only about 80 per cent of that for positive ions near the surface.

(8) CONCENTRATION OF IONS, DEPENDENCE UPON RATES OF FORMATION, DESTRUCTION, ETC.

When the rate of formation or introduction of ions into a given space is not balanced by the rate of destruction, removal, etc., the ionic density changes at a rate (dn_1/dt, dn_2/dt, dN_1/dt, or dN_2/dt) for the respective ion-types, which may be expressed as follows:
For positive small ions

$$dn_1/dt = q_1 - \alpha n_1 n_2 - \eta_{10} n_1 N_0 - \eta_{12} n_1 N_2 \tag{1}$$

For negative small ions

$$dn_2/dt = q_2 - \alpha n_1 n_2 - \eta_{20} n_2 N_0 - \eta_{21} n_2 N_1 \tag{2}$$

For positive large ions

$$dN_1/dt = Q_1 + \eta_{10} n_1 N_0 - \eta_{21} n_2 N_1 - \gamma N_1 N_2 \tag{3}$$

For negative large ions

$$dN_2/dt = Q_2 + \eta_{20} n_2 N_0 - \eta_{12} n_1 N_2 - \gamma N_1 N_2 \tag{4}$$

For uncharged nuclei

$$dN_0/dt = Q_0 + \eta_{12} n_1 N_2 + \eta_{21} n_2 N_1 + 2\gamma N_1 N_2 - \eta_{10} n_1 N_0 - \eta_{20} n_2 N_0 \tag{5}$$

The terms, q_1 and q_2, here represent the net rate at which the concentration of small ions increases as a result of ionization, eddy-diffusion, and other forms of migration. Q_1 and Q_2, which represent corresponding rates for large ions, together with the rate, Q_0, for neutral nuclei, doubtless depend chiefly upon eddy-diffusion and migration effected by other mechanical means. The coefficient of the fourth term in the right-hand member of equation (5) should be unity if the combination of large ions results in agglomeration. Investigations of Kennedy [649] indicate that the number of nuclei decreases chiefly by agglomeration and that this occurs just as readily when the nuclei are all neutral as when half or more are charged. That aspect is left out of consideration here because, as has already been seen, the term $\gamma N_1 N_2$ may be neglected in most circumstances if Kennedy's value of γ [649, p. 58], namely, 6×10^{-10}, is applicable. However, if the much larger value, namely, 1.7×10^{-8}, estimated by Hogg, is eventually verified, then the circumstances in which this term is negligible would be considerably restricted. Perhaps Hogg's result may stimulate a repetition of Kennedy's experiments with respect to this constant. Intermediate ions and ions with more than one charge are assumed to play a negligible rôle here. Although this is not always permissible [641, pp. 1–55], yet as a first approximation it seems to be justified.

There is evidence for assuming that the total number of nuclei, N, per cc may be expressed [584; 641, pp. 1–55; 657] by

$$N = N_0 + N_1 + N_2 \tag{6}$$

Then from (3), (4), (5), and (6)

$$dN/dt = Q_0 + Q_1 + Q_2 \tag{7}$$

When each ion has a single charge [584, 657] and when small ions and large ions only are present, the net electric charge per cc, ρ, is given by

$$\rho = e(n_1 - n_2 + N_1 - N_2) \tag{8}$$

Then from (1), (2), (3), (4), and (8)

$$d\rho/dt = e(q_1 - q_2 + Q_1 - Q_2) \tag{9}$$

These relations are considerably simplified if it is assumed that $Q_1 = Q_2 = Q_0 = 0$, from which it follows (*a*) that $q_1 = q_2$ [see remarks following equation (14)], (*b*) that the space-charge, ρ, does not vary with time, and (*c*) that the concentration of nuclei is constant. The assumption that the Q's are negligible doubtless imposes important restrictions upon the relations which depend upon this assumption. It is not unusual in the vicinity of cities for N to change at an average rate of 10,000 nuclei/cc/hour for several hours, in which case $(Q_1 + Q_2 + Q_0) = 3$ nuclei/cc/sec, which is not negligible when q is small. Kennedy also found by experiment that nuclei, whether charged or uncharged, decrease at a rate $dN/dt = \delta N^2$, where $\delta = 1.4 \times 10^{-9}$ per sec. This can come into account when N approaches large values. Thus for $N = 50{,}000$, $\delta N^2 = 3.5$ nuclei/cc/sec.

When it is further assumed that the ionic density in the space considered is constant, that is, when $dn_1/dt = dn_2/dt = dN_1/dt = dN_2/dt = 0$, equations (3) and (4) lead to the relations as in equations (10).

$$\left.\begin{aligned} N_0/N_1 &= (\eta_{21}/\eta_{10})(n_2/n_1) = 1/az \\ N_0/N_2 &= (\eta_{12}/\eta_{20})(n_1/n_2) = z/b \\ N_1/N_2 &= (\eta_{10}/\eta_{20})(\eta_{12}/\eta_{21})(n_1/n_2)^2 = az^2/b \end{aligned}\right\} \tag{10}$$

Also
$$R = N_0/[(N_1 + N_2)/2] = 2/(az + b/z) \tag{11}$$
and
$$S = N_0/N = 1/(1 + az + b/z) \tag{12}$$

where $z = n_1/n_2$, $a = \eta_{10}/\eta_{21}$, and $b = \eta_{20}/\eta_{12}$. According to equation (12) $S \doteq 0$ when $z \doteq 0$ or when $z \doteq \infty$. Actual cases are observed (see Figs. 13 and 15) in which z approaches 0 or ∞, that is, negative small ions or positive small ions preponderate, respectively. The nuclei should all become negatively charged in the first of these alternatives and positively charged in the second, provided z continues at either of these extreme values long enough.

As derived in these relations, R is related to S as follows

$$S = 1/(1 + 2/R)$$

However, S is frequently determined experimentally by a method that does not involve any assumptions as to the charge on the large ion. On the other hand, R may be determined from measurements of N and of N_1 and N_2. Those of N_1 and N_2 involve the assumption that each ion carries a single elementary charge. Now, if some of the ions have more than one charge, then the value of R obtained in this way will be less than that which is required by the relation with S. Comparisons of R with S, when these are determined by the two different methods, are a test of the assumption that large ions are singly charged and that large ions all act as nuclei. On the whole, such comparisons seem to support these assumptions fairly well.

Comparisons of observations of z with those for N_1/N_2, N_0/N_1, N_0/N_2, R, or S should help to determine whether the assumptions implied in the relations (1) to (4) and the additional simplifying assumptions, are justified. More extensive comparisons of that sort than can be based on data at present available are desirable. However, it does seem that N_1/N_2 tends to approach unity. It should then follow from (10) that n_1/n_2 tends to be a constant which depends upon the coefficients of combination and attachment. Although values of z determined from measurements of n_1 and n_2 made at a considerable number of places show a somewhat striking tendency to approach an average of about 1.25 [489], yet there are notable exceptions. Thus, for example, Sherman found at College, Alaska [549], that n_1/n_2, as inferred from measured values of conductivity, depends on field-strength, which is doubtless a manifestation of the electrode-effect. The dependence on field-strength was found to be greater in winter when the wind-velocity and doubtless eddy-diffusion are both small at that station. Perhaps where nuclei are plentiful—hence N_1, N_2, and N_0 large—and eddy-diffusion great enough, the relation (10) is approximately satisfied.

More determinations of R and S than of N_1/N_2 are available for study. The expressions (11) and (12) for R and S would require that $R \overset{<}{=} 1/\sqrt{ab}$ and $S \overset{<}{=} 1/(1 + 2\sqrt{ab})$. The equal sign applies when $N_1/N_2 = 1$. Thus the proportion of nuclei which are uncharged is greatest when the proportion that are charged positively is equal to that of those charged negatively. Using in these expressions for R and S the values for the coefficients given (*a*) by Nolan and de Sachy and (*b*) by Scrase, one obtains: $0 \leqq R \gtreqless 1.28$ or 3.34 and $0 \leqq S \gtreqless 0.39$ or 0.62. The values of R that are determined from observations vary considerably but the magnitude most frequently observed lies between 2 and 3. Most of the mean values of S, determined at different places, seem to lie within the range 0.50 to 0.80, with a mean of 0.64. A comparison of these with the limiting values for R and S indicates that coefficients η are to be preferred which yield a smaller value for the ratio $\eta_{10}\eta_{20}/\eta_{12}\eta_{21}$ than do those which often are employed.

Possibly when the nuclei-content is small, coefficients for which that ratio is larger are applicable. Israël [646] finds that although R is independent of the nuclei-content, N, when that is large, yet for N less than 2,000 per cc, R diminishes rapidly and approaches zero for $N \doteq 1{,}000$. Schachl [670] frequently observed $N_0 = 0$ (namely, all nuclei charged) when N was less than 800, thus verifying the findings of Israël. These observations seem to support the view that the "electrode-effect" becomes manifest in the ratios N_1/N_2 and n_1/n_2, when the content of nuclei is small but that it does not come into evidence when that content is large. Other suggestions might be made in the way of an explanation of these observations, but it is the purpose here simply to direct attention to this problem. This comparison seems to show (*a*) that the coefficients probably vary as the character or size of the nuclei or other conditions vary, (*b*) that coefficients suitable for the more usual conditions have not yet been determined, or else (*c*) that the equilibrium-relations require modification.

When the ionic density is steady and the other specified simplifying assumptions are satisfied, then equations (1) and (2) together with the relations in (10) yield the following:

$$q_1 = \alpha n_1 n_2 + (\eta_{10}z/\eta_{20} + 1)\eta_{12}n_1N_2 \tag{13}$$

$$q_2 = \alpha n_1 n_2 + (\eta_{20}/\eta_{10}z + 1)\eta_{21}n_2N_1 \tag{14}$$

The second term in the right-hand member of (13) is however equal to the corresponding term in (14) when the last of the relations in (10) is satisfied. Therefore, when the ionic density of both large and small ions does not vary with time and when $Q_1 = Q_2 = 0$, it follows that $q_1 = q_2 = q$.

Equations (3), (4), and (6), under the simplifying assumptions stated above, also yield the following relations between large ions and the total number of nuclei.

$$N_0 = (z/bD)N \tag{15}$$

$$N_1 = (az^2/bD)N \tag{16}$$

$$N_2 = (1/D)N \tag{17}$$

where $D = N/N_2 = (az^2/b + z/b + 1)$. When these equivalents are substituted in the simplified forms of equations (1) and (2), both reduce to one expression, namely

$$q = \alpha n_1 n_2 + (\eta_{12}/D)(\eta_{10} z/\eta_{20} + 1) n_1 N \tag{18}$$

The relations (13) and (18) are very important aids in the study of what may be called the "ion-population problem," despite the limitations imposed upon them by the several assumptions which were made in order to obtain manageable relations. Their effectiveness is enhanced when the observations are planned and the data marshaled in such a way as to eliminate effects of factors that are not comprehended by the relations. Thus, for example, although a set of circumstances in which the ionic density for all types of ions is steady is not met with frequently (see, for example, the reproductions of continuous records of air-conductivity, Figs. 12 to 15), yet if averages for an hour or for longer periods of time are considered, the usual unsteadiness in the state of ionization is less serious. Also the assumption that only two groups of ions—small and large ions—are extant and that the mean size, or mobility, of ions in each of these groups is constant, is more likely to be justified when dealing with a mass of observations, by suitable statistical methods, than when a few scattered observations are considered. However, the effects of factors which tend to be systematic are not necessarily eliminated by a statistical treatment of a mass of data. The effects of the electric field and of eddy-diffusion and, in some situations, the effect of straight winds upon the distribution of the ions and nuclei near the Earth are doubtless of this character. That the influence of these factors is generally negligible remains yet to be established.

A further simplification of these relations which has proved fairly satisfactory in many cases is effected if one takes $N_1/N_2 \doteq 1$ and $\eta_{10}/\eta_{20} \doteq \eta_{12}/\eta_{21}$. It then follows that $z \doteq \eta_{20}/\eta_{10}$ and (13) take the form

$$q = \alpha' n^2 + 2\eta_{12} n_1 N_2 \tag{19}$$

where $\alpha' = \alpha/z = \alpha\eta_{10}/\eta_{20}$ and equation (18) becomes

$$q = \alpha' n^2 + \beta' n N \tag{20}$$

where $\beta' = 2\eta_{12}/(2 + \eta_{12}/\eta_{10})$.

As has already been seen in a specific case, $\alpha' n^2$ is negligible when N_1, N_2, and N have values of the magnitude often found over land, and especially near centers of population. For these circumstances equations (19) and (20) say that the ionic density for small ions, n, varies inversely as that for large ions, N_1 or N_2, or as the content of nuclei, N, provided the rate of ion-formation, q, is relatively constant. The data for the mean diurnal variation of small ions and of large ions at Washington, D. C., exhibited graphically in Figure 3, definitely show such a reciprocal relation. Clearly the diurnal variation in n at that place arises in large measure from a variation in the large-ion content.

The rate of ion-production, q, may be calculated from the data in Figure 3, with the aid of equation (19), provided the values of the coefficients are known. The mean values of n_1 and N_1 from these graphs are 170 and 6,000, for the season October to March, respectively, and 200 and 4,000 for April to September, respectively. For $\eta_{12} = 8.7 \times 10^{-6}$ (Nolan and de Sachy), q is $18I$ for the first pair of values and $14I$ for the second, whereas for $\eta_{12} = 2.4 \times 10^{-6}$ (Scrase), q is $5I$ and $4I$ for the respective seasons. The average value of q determined at that place from the rate of ion-formation in a very thin-walled chamber is about 6 to $8I$.

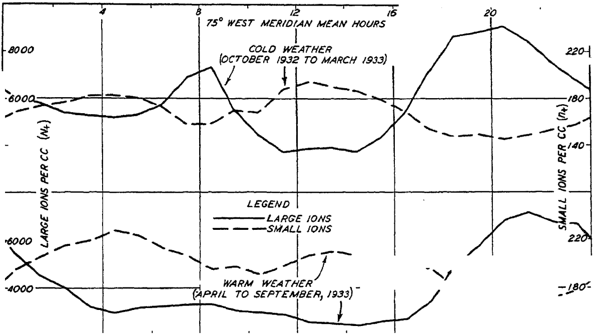


FIG. 3.—Seasonal diurnal-course in positive large ions and positive small ions—cold weather (October, 1932, to March, 1933) and warm weather (April to September, 1933), Washington, D. C.

That a relation of the form of equation (20) with both terms of the right-hand member included is sometimes required to fit observations made on land of n, or of the conductivity, λ, and of N, is illustrated by Figure 4. Ordinates there represent λ or n—the latter derived from the former—and the abscissas represent N as measured with an Aitken [552] pocket "dust-counter." Each of the points marked with a circle corresponds to the mean of 20 observations made at the Watheroo Magnetic Observatory from January to March, 1929, and reported by Builder [627]. The graph is constructed in accordance with equation (20). The recombination-coefficient α was taken as 1.6×10^{-6}, q was assumed to be constant, and the constants q and β' were adjusted so as to give the best fit. The constants obtained in this way are: $q = 2.46I$ and $\beta' = 1.25 \times 10^{-6}$. Data obtained by Wait [1303] at the same place during the latter part of

February and through March and April, 1924, when examined in this way yield comparable values for q and β'. Although a somewhat different examination of these and other data has led some investigators to conclude that either q increases as N increases or else a different law of combination and of attachment applies [660; 662, pp. 49–59], yet this comparison seems to indicate that in the average over a sufficient period of time q may be regarded as constant and the simple expression for equilibrium, in the form of equation (20), may be taken adequately to represent the relation between the observations of conductivity and those of nuclei at that place, provided a rate of ionization as small as 3 to $4I$ and a value of β' as small as 1.25×10^{-6} may be granted. Several other lines of evidence previously mentioned seem to demand a value of β', or of the coefficients upon which

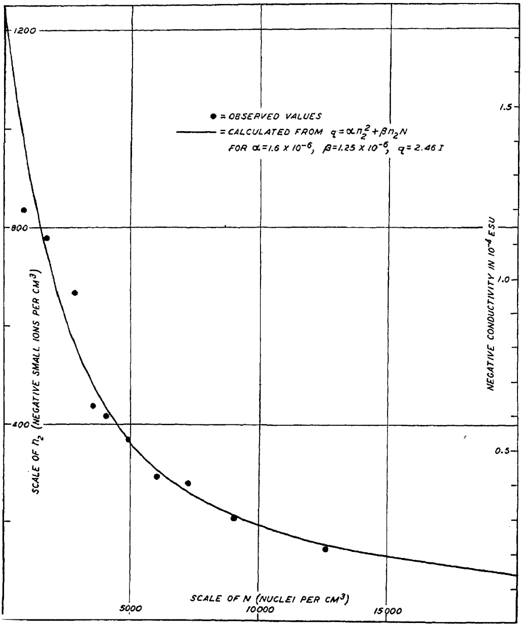


FIG. 4.—Relation between nuclei and negative conductivity, or derived small ions, Watheroo, Western Australia.

it depends, which is as small as or even smaller than this. A value of q as small as $3I$, although somewhat unexpected is not definitely excluded at Watheroo where the surface is covered to a considerable depth with sand that may contain relatively little radioactive matter. This, however, is a matter which can be decided when measurements of the ionization in a thin-walled chamber, or other reliable measurements of q, are made at that place. The general need of measurements of q is further emphasized by the considerable divergence of opinion as to what constitutes a reasonable value of that quantity. Other investigations will doubtless also be required in order to ascertain whether some of the factors which were deliberately neglected in deriving the simple form of the equilibrium-relations, or others not generally suspected as being important, require consideration. Investigations aimed in that direction are in progress at a number of places.

The *mean life of an ion* is a conception which is often convenient when considering aspects of the ion-population. The mean life of the electron in air is indicated from measurements by Bradbury [1285] to be less than 10^{-5} sec at normal temperature and pressure and for electric fields such as prevail in fair weather. The life of a small ion may be said to begin at the instant when an electron becomes detached from, or attached to, a neutral molecule or aggregate and in the case of a small ion it ends when this particular ion next becomes electrically neutral. The free life of an electron may similarly be defined as the time between detachment and the next attachment of an electron to a molecule.

Expressions for estimating the mean life of an ion are derived from the equilibrium-relations by the usual mathematical device for obtaining a mean value. One finds in this way for the mean life, ϑ, of a small ion the alternative expressions as in equation (21)

$$\vartheta_1 = n_1/q = 1/(\alpha n_2 + g\eta_{12}N_2) = 1/(\alpha n_2 + g\eta_{12}N/D) \qquad (21)$$

where $g = (\eta_{10}z/\eta_{20} + 1)$; D has already been defined in connection with relations (15) to (17).

When the concentration of nuclei is sufficiently small, $\vartheta_1 = 1/\alpha n_2$ and when further $n_1 = n_2$, we have

$$\vartheta_1 = 1/\sqrt{\alpha q} \qquad (21a)$$

When the concentration of nuclei is large, $\vartheta_1 = 1/g\eta_{12}N_2 = D/g\eta_{12}N$. For the simplifying assumptions employed in obtaining equations (19) and (20)

$$\vartheta_1 = 1/2\eta_{12}N_2 = 1/\beta' N \qquad (21b)$$

Values for the mean life of the small ion, obtained from such relations as well as from more direct experimental [634, 635, 636; 641, pp. 1–55;

662, pp. 40–48; 672] determinations, vary over wide limits. The mean life of the small ion at sea appears to be 300 sec or more. Near cities where the concentration of nuclei is large it sometimes is as small as ten sec. One minute may be regarded as an average at most places on land for which this can be determined with the data now available. Values for the mean life of the small ions in the troposphere and stratosphere, calculated from values of n_1 and q, are shown in Figure 6. ϑ increases in the first 2.5 km to about 300 sec, then decreases to about 100 sec at ten km, remains nearly constant in the next six km, then increases again to a secondary maximum of 160 sec at about 20 km, after which smaller values are found up to the highest altitude of observation.

The mean life, θ, of the large ion may be calculated by the following formulas, which are derived in a manner similar to that indicated for the case of small ions.

$$\theta_1 = 1/(\eta_{21}n_2 + \gamma N_2) = N_1/(\eta_{10}n_1N_0) \tag{22}$$

or for γN_2 much less than $\eta_{21}n_2$

$$\theta_1 = 1/(\eta_{21}n_2) \tag{22a}$$

or from (21) and (22*a*) it follows that

$$\theta_1/\vartheta_1 = q/\eta_{21}n_1n_2 \tag{22b}$$

Since $\eta_{21}n_1n_2$ has about the same value as αn_1n_2 and since, as already seen, the latter is quite small compared with q at many places on land, it therefore appears that the mean life of a large ion is much greater than that of the small ion when condensation-nuclei are abundant. From these relations it is estimated that over the open ocean the mean life of the large ion is about the same as that of the small ion, say about 300 sec, or five minutes, but over land it doubtless ranges from five minutes up to an hour or more. Thus the mean life of the large ion at some places, for which the requisite data are available, is probably between one and two orders of magnitude greater than is that for small ions.

Because of the relatively short mean life of the small ion one may expect that changes in the concentration, n, of these ions will follow without much lag and without much diminution of amplitude the changes in the immediately controlling factors, namely, q, N_1, N_2, or N.

That variations of short duration in q are well reflected in the values of n, but are not conspicuously manifest in N_1 or N_2, is well illustrated in the simultaneous registrations of the concentration of small ions and of large ions made at Washington, D. C., by Wait and Torreson. During some intervals when the high-voltage equipment that is used for accelerating protons, in connection with investigations of the atom, is in operation at a distance of about 75 meters from the site where the atmospheric-electric registrations are made, the ionization, q, increases many fold, and n increases simultaneously in a conspicuous manner. However, the concentration of large ions undergoes no appreciable change at such times. Thus $dN_1/dt \doteq dN_2/dt \doteq 0$, which implies that large ions are being destroyed by combination with small ions at the same rate that large ions are formed by the attachment of small ions to neutral nuclei.

On the other hand, when a change in the concentration of large ions is registered, a corresponding change in the concentration of small ions usually appears, as is illustrated by Figure 3.

It is found at Washington, D. C., by Wait and Torreson that the diurnal, or shorter-period, variations in the concentration of small ions are more closely correlated with variations in large ions than with variations in nuclei. Such a result is to be expected if the mean life of the uncharged nucleus is considerably greater than that of a large ion or, in terms of the coefficients, if η_{10} and η_{20} are considerably less than η_{12} and η_{21}. Other observations which point to the last condition have been mentioned previously. Good correlation between the concentration of small ions and that of nuclei, such as is seen in Figure 4, is apparently found when the effects of variations of short period, in both N and q, are largely eliminated from the data. The latter is in part accomplished by using means of a considerable number of observations. When the average concentration of nuclei is small, variations in the small-ion content may be expected to reflect variations in q more than variations in N so that correlations between n and N are of low degree in such cases.

The study of these relations between the ion-forming and ion-destroying processes is one of the principal phases of atmospheric-electric investigations in recent years. These investigations have consisted of two general aspects as follows: (*a*) Attempts to determine whether the relations, in the simplified form usually employed, are consistent with the observed facts; and (*b*) accepting the relations attempt is made to determine factors, not readily accessible to measurement, which affect the small-ion content.

Something of the character of the results realized from these investigations has been indicated in the foregoing paragraphs. In summarizing, it may be stated that the expressions for the relations between ionic density and the factors which control it have considerable merit, provided due consideration is given to their avowed limitations. More investigation is required to determine the limits of their applicability. The magnitude of the constants, the degree to which these are really constant, how they depend upon temperature, pressure, and other factors are matters which require further investigation. When the constants are adequately determined, such relations should be very useful for detecting and for ascertaining the magnitude of factors which cannot be measured directly or if so only with great difficulty. This is illustrated by tentative conclusions regarding the distribution of nuclei in the high atmosphere, derived from the observations of conductivity and cosmic radiation with the aid of these relations (see Fig. 7). These results are tentative because the dependence of the coefficients upon pressure is not known.

One puzzle for which an approximate solution was obtained as soon as account was taken of the rôle of large ions and nuclei in the equilibrium-relations may be presented as follows: The ionic density at sea was known to be as great as, or greater than, that at places on land at about sea-level, but it was also known that the rate of ion-formation at sea is considerably less than that at land-stations. However, when the importance of nuclei in reducing the mean life of the small ion was quantitatively considered, this apparent paradox was resolved. Other examples of phenomena which are clarified by these considerations will be given in connection with descriptions which are to follow of some observed features of the electric state of the atmosphere.

(9) CONCENTRATION OF IONS AND NUCLEI, OBSERVED VALUES

Actual values of n_1 and n_2 measured over land differ so much from place to place and from time to time that an average of all values is of questionable significance. Furthermore, many of these values are now thought to be too large owing to an error in the measurements, not recognized earlier, that comes from collecting large and intermediate ions in addition to small ions. The averages of reported values are, approximately, $n_1 = 750$, $n_2 = 650$, but some of the individual values are as low as 50 while others exceed 1,000. At sea the range is much less, but the average values are about the same, namely, $n_1 = 600$, $n_2 = 500$. The range in the values of large-ion density is also large, namely, 300 to 50,000 per cc but observations are available for so few places that a general average of all has no significance. In the outskirts of Washington, D. C., the average is about 5,000 pairs of large ions/cc. At Glencree, Ireland [660], located in open country 18 km south of Dublin, the concentration of large ions depends much upon wind-direction, averaging 1,500 ion-pairs/cc for winds from north, northeast, and east, and only 314 ion-pairs/cc for winds from all other directions.

The range in the observed number of nuclei/cc is much greater than that for large ions. In a collection made by Landsberg [1294] of all available data, the values range from 0 to 4,000,000 per cc. The significance of averages of these measurements is also limited. The average in "cities" is about 150,000 per cc, in "towns" it is about one-fourth of that in cities, while in open country it is about six per cent of that in cities. These relative values apply to places at about sea-level. The number of nuclei in the air over mountains decreases with elevation. At elevations greater than 2,000 meters the number is only about one-tenth that at sea-level in open country and is about the same as is found over the open ocean, namely, about 900 per cc.

If one calculates the value n_1 from the relation $n_1 = q/\beta' N$ with $q = 9.5I$, estimated by Hess as the average for places on land, and $N = 10{,}000$, the approximate average for open country according to Landsberg, one obtains $n_1 = 170$ or 1,200 ions/cc—the first for values of the coefficients which enter through β', by Nolan and de Sachy, the second for those by Scrase. The observed values of n_1 usually fall within these limits.

The average values of q, n_1, n_2, z, and N, observed at sea, may be used to test the relation $q = (\alpha' n_1^2 + \beta' n_1 N)$ for given values of the coefficients or, taking an accepted value for α, the value of β' may be estimated. The values of q derived from many measurements of the rate of ion-formation in a closed copper chamber with walls about one mm thick, which were made on cruises of the *Carnegie,* average $2.2I$. Measurements of the intensity of cosmic radiation indicate that that agency may produce ions at a rate of about $1.5I$ at sea-level. Both estimates are somewhat uncertain but a value of $2I$ may not be far from correct. The average of individual values of z is 1.23. In order that equation (20) be consistent with this value of z it is necessary that $\eta_{10}/\eta_{20} = 1/z = 0.81$, whereas this ratio is 0.90 according to Nolan and de Sachy and 0.54 according to Scrase. It is to be noted that for oceanic conditions the term $\alpha n_1 n_2$ is not negligible but amounts to $0.48I$ for average conditions at sea or about 25 per cent of the value of q. The value of β' derived from the foregoing values of q, n_1, n_2, and N with the aid of equation (20) is 3.2×10^{-6}. No numerical significance should be attached to a value derived in this way simply for the purpose of illustration, but it is of some interest that this lies between the values of β', 5.3×10^{-6}, and 0.78×10^{-6}, obtained from the η's of Nolan and de Sachy and of Scrase, respectively.

The magnitude of the rate of ion-formation, of the rate of destruction or transformation, and the extent and manner in which these processes vary, as has been seen, determine the concentration of small ions and the manner in which the latter varies. Since it was also seen that the mobility of the small ions apparently undergoes only minor change near the Earth's surface, it will be evident that the electrical conductivity of the air there depends chiefly upon the mean life, ϑ, of the small ion which in turn is determined by the rate at which small ions are formed and the rate at which they are destroyed, the latter often depending chiefly upon the amount of pollution in the air in the form of nuclei of condensation. Migration of ions has also been indicated as a factor which determines to some extent the concentration of small ions. The latter is probably a subordinate factor under average fair-weather conditions but the data from which this conclusion is derived are so meager that this may be regarded as a problem for further investigation. This feature will however be given a little further consideration under the topic "space-charge."

The concentration of small ions in the free atmosphere generally increases with altitude throughout the troposphere. The values obtained from measurements made during 13 balloon-flights are shown in Figure 5. These results are derived from actual measurements of air-conductivity. Although on a few flights direct measurements of the ionic density were made by Gerdien and Wigand, yet such measurements are subject to more uncertainty than measurements of air-conductivity, especially so with the equipment used earlier, so that values derived from the measurements of conductivity may be regarded with somewhat more confidence. Although there is considerable scatter in the values measured at any given altitude, there is, in general, an increase of roughly 1,000 ions/cc for each two-km increase of altitude.

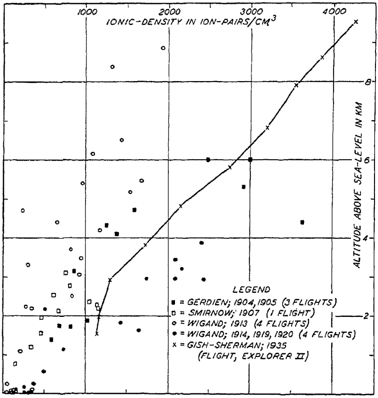


Fig. 5.—Ionic density in the troposphere from measurements of air-conductivity on 13 balloon-flights.

On the flight of the stratosphere balloon *Explorer II* measurements of air-conductivity were carried to an altitude of about 22 km. The ionic densities derived from those measurements are shown in Figure 6. The increase of ionic density continues some distance into the stratosphere but at about 15 km a maximum density of about 5,000 ions/cc is reached after which a decrease sets in so that at the maximum altitude the density is 2,000 ions/cc.

The increase of ionic density in the troposphere is associated with the increase in the rate of ion-formation by the cosmic radiation. The decrease which follows the maximum at high altitudes seems also to follow a decrease in the rate of ion-formation. The values of the latter, cal-

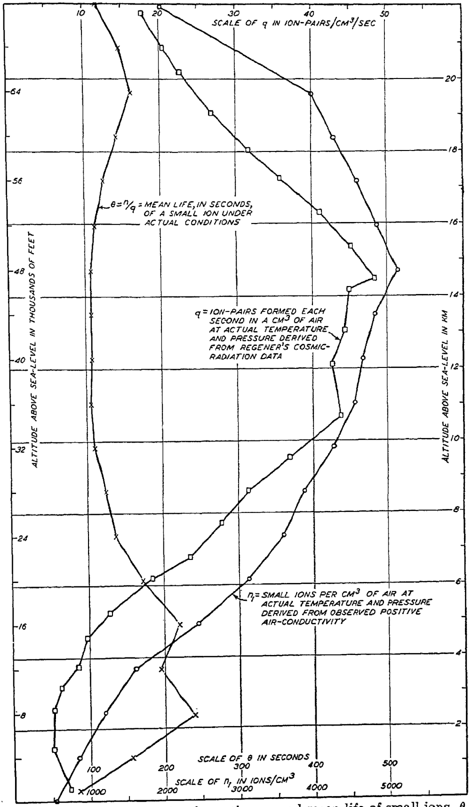


FIG. 6.—Ionic density, n, rate of ion-formation, q, and mean life of small ions, θ, in troposphere and stratosphere (*derived from measurements of air-conductivity on flight of Explorer II, and of cosmic radiation, Regener*).

culated from cosmic-radiation measurements of Regener, are shown in Figure 6. The relation between q and n is the simple one, namely, $n = \sqrt{q/\alpha}$ for the range of altitude 5 to 19 km, provided α varies directly as the 0.28 power of the pressure. In that case the mean life of the ion would be $1/\sqrt{\alpha q}$ and since it is generally thought that α varies as the pressure one should not expect to find the mean life when calculated in the more precise form ($\vartheta = n/q$) to run parallel with the value of q. The mean life calculated by the relation last indicated is also shown in this Figure. It increases in the first two km to about 240 sec which is followed

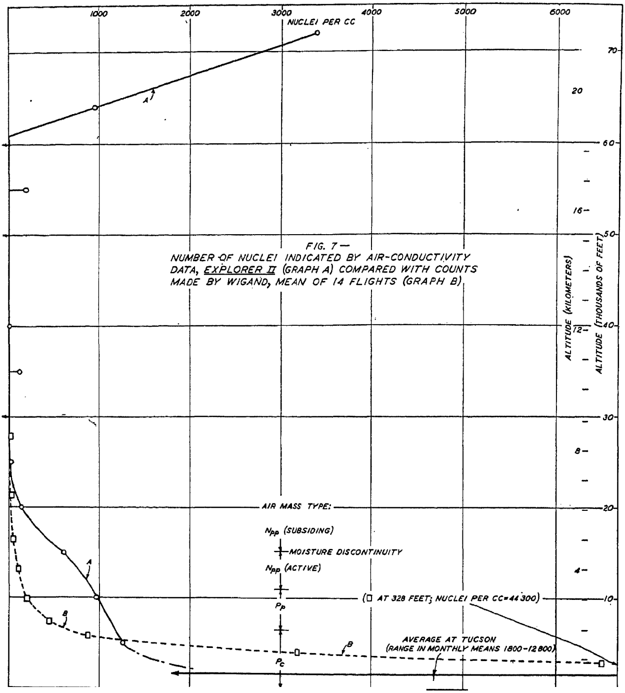


FIG. 7.—Number of nuclei indicated by air-conductivity data, *Explorer II* (graph *A*) compared with counts made by Wigand, mean of 14 flights (graph *B*).

by a decrease to nearly 100 sec at 10 km, then remaining nearly constant up to 16 km. From that point to 20 km it increases to about 150 sec, after which it decreases again. The departure of the mean life from that which might have been expected is conspicuous above 19 km. This may be attributed to the presence of nuclei in that portion of the atmosphere.

Nuclei in the free atmosphere.—Measurements made on 14 balloon-flights by Wigand indicate that the nuclei in general decrease rapidly in the first two km after which a slower decrease sets in and continues until at six or seven km the number is inappreciable. These results of Wigand are shown in Figure 7 by a broken line. There is also shown in this Figure the distribution of nuclei which is required to account for the observed relation between the concentration of ions and the rate of ion-formation, which was mentioned in the previous paragraph. The calculation of that distribution, however, required assumptions as to the value of the coefficients of combination and attachment and also the assumption that these coefficients vary with pressure and temperature in the same manner as the coefficient α. The latter assumption is especially open to question. However, these calculations may, despite such uncertainties, have some qualitative significance. The principal unexpected feature is the bank of nuclei which apparently extends from an altitude of about 19 km up to the highest level reached on this flight. That nuclei may be present in the high atmosphere has been indicated by the presence there of clouds. The height of this apparent bank of nuclei coincides approximately with the lower levels at which mother-of-pearl clouds are observed. It is also at this level that the concentration of ozone as measured on this flight began to increase conspicuously with altitude. The recent spectroscopic detection, by Adel and Lampland [1282], of nitrogen pentoxide (N_2O_5) at altitudes of 16 to 40 km in the atmosphere suggests that nuclei may be formed in that region by the combinations of oxygen and nitrogen that are effected by ultraviolet light. Instead of establishing the existence of nuclei this tentative interpretation rather serves to illustrate some possible contributions which measurements of air-conductivity may make to other phases of geophysics when the constants in the ionic equilibrium-relations and their dependence on temperature and pressure are adequately known.

(10) THE ELECTRICAL CONDUCTIVITY OF AIR AT THE SURFACE

Like the concentration of small ions, the electrical conductivity of air at the surface over land varies from place to place, being generally much less in the vicinity of large cities than in open country, the values for the total conductivity, λ, ranging from 0.2×10^{-4} to 5×10^{-4} ESU. It also undergoes an annual and a diurnal variation at most land-stations and is subject to various irregular fluctuations.

The magnitude and character of the annual variation of conductivity are not uniform but depend considerably upon local circumstances. However, in general, the conductivity tends to be greater in summer than in winter. This may be attributed in part to the higher temperature in summer which results in an increase in mobility and tends also to increase the concentration of small ions for a given intensity of the ionizers. Calculations indicate that for an annual temperature-range of 30°C (annual range in a large part of the United States, 20° to 30°C) the annual range in conductivity due to temperature alone may amount to 18 per cent of the mean value. This is much less than that generally found. Furthermore, a comparison of data like those in Figure 3 indicates that the annual variation depends chiefly upon other circumstances at some places and that an important one of these is the variation of atmospheric pollution. The latter is reflected in the observed variation of large-ion concentration, which has a minimum in summer and a maximum in winter at Washington, and doubtless also at other centers of population where residences are heated in winter. Another factor in λ is the rate of ion-formation, which in turn depends upon the radioactive content of air. The latter seems generally to be greater in summer than in winter, a circumstance which doubtless contributes to the annual variation in air-conductivity. It may be that in open country the latter is the chief controlling influence. This cannot be decided until more observations of the number of nuclei, or of large ions, and of the rate of ion-formation are made in open country simultaneously with observations of conductivity.

The *diurnal variation* in conductivity at stations on land is also very dependent upon local circumstances, particularly those which affect the rate of formation and the rate of destruction of small ions to an extent which varies somewhat regularly during the day. From what has already been said about the dependence of conductivity upon the concentration of small ions it follows that the diurnal variation of conductivity should be much like that for small ions. Hence the example of the latter, which is described in an earlier paragraph and illustrated in Figure 3, may also serve to indicate the character of the diurnal variation in conductivity at Washington and the extent to which it depends upon the variation in the concentration of large ions or, indirectly, upon the degree of pollution of the air. The latter obviously plays a dominant rôle there. Even the early morning maximum in conductivity, which has been regarded as a feature of more than local significance, seems to be largely the result of diminished pollution.

Other examples which will serve further to illustrate the diurnal variation, as well as other fluctuations, in conductivity are provided by the continuous registrations of air-conductivity for a quiet day and for a stormy day at each of the two magnetic observatories of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. In the selection of sites for these observatories the first requirement was that they should be far enough removed from circumstances that exercise a distorting influence upon the magnetic and electric phenomena, the investigation of which these observatories are designed to further, that even the encroachment of such circumstances in the future should be unlikely. The sites are consequently far from centers of population.

The Watheroo Observatory is located on a level sandy plain in a semi-arid region of Western Australia in latitude 30°.32 south and longitude 115°.88 east; it is 200 km north of Perth, 19 km west of the railway station at Watheroo, and 89 km from the western sea-coast of Australia. The location is therefore one which should be relatively free from atmospheric pollution and the attendant abundance of nuclei. Smoke from brush-fires does however conspicuously pollute the air at intervals during the dry season—which corresponds approximately to northern winter—but in the wet season (August) when the records shown here were obtained pollution is not introduced from that source.

The Huancayo Observatory is located in a broad valley between ranges of the Andes Mountains in Peru at an elevation of 3,353 meters; it is 174 km east of Lima and 14.5 km west of the village of Huancayo in latitude 12°.05 south, and longitude 75°.34 west. Although this site might be thought to be exempt from artificial pollution of the atmosphere, that is apparently not the case, for it is now established that when the general air-circulation and other conditions are suitable, air with a high content of nuclei reaches this place doubtless coming from copper smelters at Aroya about 124 km (77 miles) farther up the valley.

The difference in the character of the diurnal variation of conductivity at these two places is very conspicuous. At Watheroo (Figs. 12 and 13) the variation is gradual throughout the day. The maximum, at about 8^h, is about twice the minimum which occurs shortly after midday. At Huancayo (Figs. 14 and 15) the values are conspicuously high during the greater part of the night on most "quiet" days, especially during the five months of the dry season (May to September). These values are of about the magnitude to be expected at a station of such altitude but in daytime they are much smaller. The change from night-time to daytime values occurs abruptly. Within approximately an hour, centering at about 7^h, the conductivity suffers a decrease of about 80 per cent. That type of diurnal variation, although repeated day after day during the dry season, does not appear at times of storm, as is illustrated by Figure 15, or when the wind-velocity exceeds six to eight miles per hour (three meters per sec). The diurnal variation at Watheroo seems to be modified little if at all on days of storm (Fig. 13) except during the actual period of storm. This suggests that it depends upon more general circumstances than those at Huancayo and that it may therefore be more representative of undisturbed conditions at a station in the open country.

The diurnal variation in conductivity at Huancayo is definitely anomalous but it is interesting as an example of a marked response of conductivity to a combination of meteorological and other circumstances. This response is apparently effected in the following manner.

The large values of conductivity at night occur when a shallow stratum of cool quiet air develops near the surface. This implies very little mixing of the air below with that above a certain level (level of temperature-inversion), so that radioactive matter coming from the Earth is in a sense trapped in the shallow surface-stratum. Furthermore, the air which drains down the mountain-slopes to form the stable surface-stratum during the night doubtless carries fewer nuclei and may also be richer in radioactive matter, although the latter is apparently not a necessary condition. These circumstances favor the development of a maximum conductivity at night.

The air which overruns the surface-stratum apparently flows in a stream down the valley and carries an abundance of nuclei from the principal source of these about 77 miles (124 km) up the valley. In the morning as soon as the surface-air becomes sufficiently warmed, the lower stratum is broken up and is mixed with air from higher levels. In this way the radioactive matter issuing from the Earth is dispersed to greater altitudes, thus diluting the content near the surface, and nuclei are abundantly supplied to the surface-air from higher levels. This change from the stratified to the mixed condition takes place in about an hour, and brings about the abrupt decrease in conductivity and a corresponding increase in potential-gradient at from one to two hours after sunrise.

On days of storm, or when the wind exceeds a certain velocity, the lower stratum is not developed. The conductivity is not so great at night and generally not so low during the day. This may also be explained, in part, as a result of mixing, the nuclei being dispersed to greater levels than usual. But it seems likely that other circumstances also come into account on days of storm such as the removal of nuclei from the air by rain or a reduction in their number due to departures from the usual general air-circulation, either of which favors a larger conductivity at such times.

Irregular variations of short duration may be a conspicuous feature of conductivity at times. Three classes of such variations are illustrated in the electrograms reproduced here:

(*a*) Fluctuations which last a few minutes and have a range that may reach 50 per cent of the prevailing value. These are especially conspicuous on a quiet night at Huancayo (Fig. 14) and are thought to be a result of the irregular distribution of radioactive matter in the air—a condition which is favored by the formation at that place of a shallow surface-stratum of stable air on quiet nights.

(*b*) Fluctuations which consist in the depression of the conductivity of one sign without a corresponding change in the other component. These occur only during periods of storm (Figs. 13 and 15), when the gradient is numerically very large. For large positive gradients the negative conductivity may be reduced to zero and when the gradient has a large negative value the positive conductivity may vanish. Examples of this type of fluctuation are to be seen in Figure 13, shortly after 0^h, and in Figure 15, at from 20^h to 22^h and again in the interval 14^h to 17^h. Shortly after the beginning of this last-mentioned interval the negative conductivity was reduced nearly to zero for a period of about an hour, but shortly after 15^h10^m it suddenly increased to nearly a normal value at which time, however, the positive conductivity was as suddenly depressed to a very small value. This state of affairs continued about 15 minutes. Then the relation between positive and negative conductivity was reversed for a short interval. The positive and negative conductivity alternated in this way seven times during the remainder of this storm.

(*c*) Fluctuations which consist in a marked enhancement, frequently of several fold, of at least one component of the conductivity but more often of both. These occur only at times of storm, and even then infrequently. They last only a few minutes and may fluctuate rapidly during that interval. Examples of such fluctuations are to be seen in the electrogram for negative conductivity in Figure 13, at about 18^h10^m and at about 1^h50^m, and also in the electrogram for negative conductivity in Figure 15, shortly after 22^h. Both those examples appear in the negative conductivity but that is apparently not significant.

(11) The electrical conductivity at sea

Information regarding the distribution and variation of conductivity at sea is derived chiefly from observations made on board the *Carnegie* [608, pp. 197–286]. These data show no definite evidence of a simple dependence of conductivity upon position, but near land the values are more variable both with position and with time and apparently tend to be somewhat smaller than well out over the open sea. The data seem to justify the conclusion that there is no dependence upon latitude amounting to more than a few per cent. This result is consistent with the assumptions (*a*) that the cosmic radiation is the sole ionizer at sea and (*b*) that the content of nuclei is independent of latitude, since calculations which involve these assumptions show that although the cosmic radiation is less at the magnetic equator than in high magnetic latitudes—the difference amounting to about 13 per cent in the eastern Pacific and about 21 per cent in the Indian Ocean—yet when the difference in temperature is taken into account, the average conductivity in low latitudes should not differ from that in high latitudes by more than two or three per cent. Such considerations lead one to expect that the conductivity of air over the open oceans should vary only when the concentration of nuclei varies. Observations of nuclei are not yet adequate to disclose a definite dependence upon position or to test this surmise in other ways.

Variations from year to year are apparently indicated by the data in Table 3.

TABLE 3.—*Variations from year to year in conductivity of air over open oceans*

Value	*Carnegie* cruise number		
	IV	VI	VII
Mean epoch	1916.2	1920.8	1929.1
Mean of total conductivity (in 10^{-4} ESU)	2.2	2.7	2.0

This feature merits further investigation. It implies either that the rate of ion-formation was less or that the content of nuclei was greater during the first and last than during the intermediate epochs. Either alternative presents a challenge to the investigator.

An annual variation would escape detection since there are scarcely any data available for winter, the season of rough weather at sea.

Variations from day to day occur in an irregular sequence. In the course of a month the extreme mean for a day may differ from the mean conductivity for the month by as much as 25 per cent.

A diurnal variation in the total conductivity of relatively small amplitude—about four per cent of the mean—is indicated by continuous registrations of conductivity made at sea during the last three months of cruise VII of the *Carnegie*. The character of this variation may be described with the aid of Figure 8. The ordinates there represent (*a*) positive conductivity in the uppermost graph, (*b*) negative conductivity in the second graph, (*c*) total conductivity in the third graph, and (*d*) the ratio of positive to negative conductivity in the lowermost graph. The abscissas represent the hour of day counted from Greenwich midnight, but, since the registrations were all obtained in a relatively narrow range of longitude in the northern Pacific Ocean, they also approximately represent the hour of the local day if the scale is shifted ten hours to the right so that local midnight comes at 10^h Greenwich time. Because of this restricted distribution in longitude these data do not enable one to decide whether this variation proceeds according to local or universal time. However, the former is favored by data obtained over the Atlantic Ocean earlier in this cruise by manual observations made at hourly intervals during the day on a total of 23 days. Viewed as a local-time phenomenon the positive and the total conductivity may be described as varying gradually during the day from a minimum in the afternoon to a maximum in the morning, the range from maximum to minimum being 14 per cent of the daily mean for the positive and about eight per cent for the total conductivity. The negative conductivity, however, apparently does not vary with a significant daily period. The features just described are repeated with striking fidelity in graphs constructed from subgroups (five or more days) of the data. Hence one infers that a diurnal variation in conductivity of this type may occur over considerable areas of the ocean. No entirely satisfactory way of accounting for this feature has yet been devised. Since the effects of this upon the gradient and electric conduction-current can scarcely amount to more than four per cent, the bearing of this feature upon the general problems of atmospheric electricity is doubtless of minor importance.

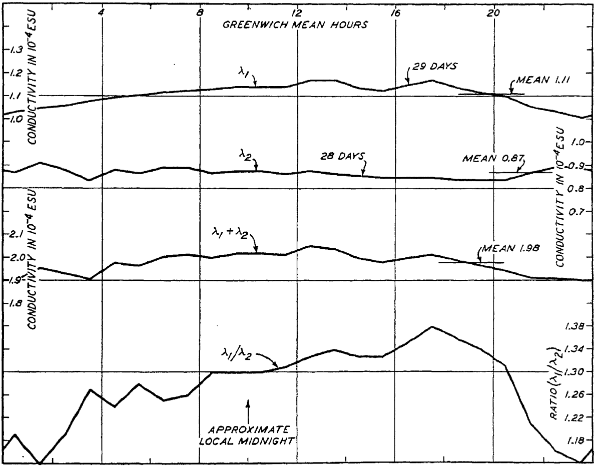


FIG. 8.—Electrical conductivity of air over northern Pacific Ocean from continuous registrations on board *Carnegie*, cruise VII, September to November, 1929.

Variations in conductivity having periods much less than a day occur less frequently and, in general, are less conspicuous at sea than at stations on land. It is chiefly because of this feature that records extending over a comparatively short period are capable of revealing periodic variations of such small amplitude as that described in the preceding paragraph. This circumstance is also very favorable for investigations of other aspects of atmospheric electricity at sea.

(12) ELECTRICAL CONDUCTIVITY IN THE FREE ATMOSPHERE

The electrical conductivity of air generally increases with altitude, although some minor exceptions to this rule have been observed. Measurements made at the Earth's surface are generally greater the higher the station above sea-level. However, such measurements are obviously unsuitable for investigating a pure altitude-effect because of the relatively large differences from place to place in circumstances which affect the conductivity, such as the content of radioactive matter and of nuclei in the air near the surface. In the discussion of these disturbing elements it was pointed out that the content of radioactive matter and that of nuclei both decrease rather rapidly with distance from the surface. Variations of conductivity both with place and with time during fair weather should therefore be smaller at points in the free atmosphere than at the surface. This expectation is indirectly verified by registrations of potential-gradient on high towers [483, p. 416; 490, part 2, p. 123].

Observations made in the free atmosphere are therefore likely to be relatively free from these local effects and the more so the greater the distance from the surface. The characteristic variation of conductivity with altitude is accordingly best determined by observations made on flights of balloons or other aircraft.

The results obtained on 13 flights, expressed in ion-concentration, have previously been shown (Fig. 5). On 12 of these flights, made in Europe, most of the observations were made at altitudes less than six km; a few were made between this and the nine-km level and were therefore within the troposphere; the other and most recent flight, however, penetrated over 11 km into the stratosphere. The results obtained on the last-mentioned flight will be used here to illustrate the variation of conductivity with altitude in the free atmosphere.

This was the notable stratosphere flight sponsored by the National Geographic Society and the United States Army Air Corps, which was made on November 11, 1935, in the balloon *Explorer II* commanded by Major Albert W. Stevens and piloted by Captain Orvil A. Anderson [1298]. The flight began near Rapid City, South Dakota, and the balloon landed in the east central part of that State. The average position was therefore near the center of the North American Continent. The continuous registration of the electrical conductivity of air was satisfactorily accomplished throughout the flight with apparatus designed and constructed at the Department of Terrestrial Magnetism of the Carnegie Institution of Washington.

The results are shown in Figure 9. The ordinates of graph *A* represent the values of positive conductivity during the ascent and those of graph *B* represent values recorded during the descent. Aside from the general increase of conductivity with altitude, one of the first features to be noted is that the values recorded on the ascent are generally less than those recorded on the descent. The only suggestion which can be offered to account for this feature is that the sample of air involved in a measurement on the ascent may have been "polluted" by its previous proximity to the large balloon, whereas on the descent the sample was taken from the uncontaminated air into which the gondola was continuously moving

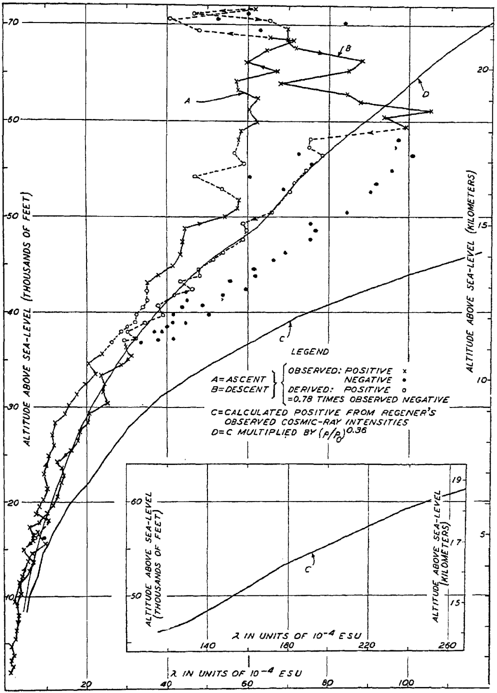


FIG. 9.—Air-conductivity, flight of *Explorer II* near Rapid City, South Dakota, November 11, 1935.

at an average rate of about 500 feet per minute. The values measured on the descent, therefore, should be the more representative of conditions prevailing in the free atmosphere. A notable departure from the general increase with altitude was found at altitudes greater than 18 or 19 km. It may be significant that this is a region where the prominent bank of ozone was observed on this flight.

Attention is next invited to the relation between values of positive and of negative conductivity—the former marked by oblique crosses, the latter by solid circles. The negative conductivity is generally greater than the positive conductivity recorded at the same level, the only significant exception being a group of three values for negative conductivity shown near the top of the chart. These values are doubtless too small since investigation shows that at about this level there was an approach to conditions for which the conductance in the Gerdien condenser was not ohmic in character when the balloon was ascending at a moderate rate. Those three values are therefore to be excluded from further consideration.

Except for the group of values just mentioned, the ratio of negative to positive conductivity is approximately constant at all altitudes where comparison is possible. This is shown by the satisfactory alignment of the points which correspond to the observed values of positive conductivity—those marked by crosses—with those which are marked by open circles. The abscissas for the latter were obtained by multiplying the observed values of negative conductivity by a constant, namely, 0.78, which is approximately the ratio of the mobility of the positive to that of the negative small ion in dry air at standard temperature and pressure.

From this observation it seems necessary to conclude that the ratio of positive to negative conductivity, under the circumstances which prevail in the free atmosphere, is constant over the range of pressures from 760 to 30 mm of mercury and, since the concentration of small positive ions must be very nearly equal to that of negative ions at a given altitude—except very near the Earth's surface—it follows that the ratio of the mobility of the negative ion to that of the positive ion in the atmosphere is approximately constant throughout that range of pressures. This is contrary to a conclusion, which is either expressed or implied in most treatises on the conduction of electricity in gases and elsewhere, and according to which the mean mobility of the negative carriers (negative ions and electrons) increases considerably relative to that of positive ions at pressures below 100 mm of mercury, presumably because electrons then begin to play a dominant rôle as carriers of negative electricity. Although that interpretation seems admissible for the actual conditions impossed on those experiments in the laboratory, which show an increase of the effective mobility of the negative carriers relative to that of positive ions at low pressures, yet it seems inadmissible for the actual circumstances in the free atmosphere except at much greater altitudes, or lower pressures, than those which have to be considered here. This conclusion does not necessarily depend wholly upon the observations of conductivity in the free atmosphere but it may also be inferred from present knowledge of the attachment-time, or mean life, of the free electron and the electron-mobility in air [1285, 1296] that the rôle of the free electron as an electrical carrier in the atmosphere is quite insignificant except at exceedingly low pressures or when the intensity of ionization is greater than has ever been directly observed in the atmosphere during fair weather.

A comparison of calculations of the conductivity in the free atmosphere with the observed values reveals several features of interest and poses problems for further investigation. In these calculations it is initially assumed that the cosmic radiation is the sole ionizer of the atmosphere and that the ions present there are practically all of the small-ion type. This is equivalent to assuming that the content of nuclei, or of other impurities which affect ionic balance in a similar manner, is negligible. The relations upon which such a calculation depends have been separately stated and discussed in earlier sections but for convenience those for the positive conductivity, λ_1, are summarized below.

$$\lambda_1 = ek_1n_1; \qquad k_1 = (k_1)_0p_0T/(pT_0); \qquad n_1 = \sqrt{q/\alpha}$$
$$q = I^0pT_0/(p_0T); \qquad \text{and} \qquad \alpha = \alpha_0(p/p_0)^x(T_0/T)$$

When these are combined

$$\lambda_1 = ek_0(p_0/p)^{(x+1)/2}(T/T_0)^{\frac{3}{2}}\sqrt{I^0/\alpha_0}$$

Evidence regarding the value of x was discussed in the section dealing with the dependence of the recombination-coefficient upon temperature and pressure.

The values for positive conductivity obtained from calculations in which x was taken as unity are represented by graph C of Figure 9. It will be noted that in every case the calculated value is greater than that observed at a corresponding altitude. A difference of this character, but decreasing with altitude, is to be expected for altitudes up to five or six km on account of the presence there of condensation-nuclei (see graph B, Fig. 7). However, it seems unlikely that the difference between the values observed and those calculated for altitudes above six km may be entirely attributed to the presence of nuclei. It would be difficult to account for the quantity and distribution of nuclei which are required for such an explanation.

If x is taken as 0.28, the calculated values, represented by graph D, Figure 9, are in satisfactory agreement with those observed on the descent from an altitude of 18 km to six km. Below six km and above 18 km the values calculated in this way are greater than those observed. This sort of disparity is quite in accord with expectation for the lower levels where nuclei are known to be present. However, there is an element of surprise in the indication that there are nuclei or other "impurities" at 18 to 22 km in sufficient abundance to destroy or to transform small ions at such a rate that the conductivity there is reduced as much as 50 per cent. There is, however, other evidence, mentioned in the section on nuclei, which appears to support this indication. Whether this interpretation is essentially correct, whether the feature thus indicated is permanent, and whether it is of wide extent, both vertically and laterally, are questions which can be answered only by more extensive observation and investigation. Those answers will doubtless have a bearing on other than electrical problems of the atmosphere. If the relatively low conductivity indicated at altitudes above 18 km should be permanent and continue to considerably higher levels, then some atmospheric-electric phenomena at the surface should be appreciably different than for the alternate case in which the conductivity generally continues to increase with altitude. An example will be given in the next section.

(13) THE ELECTRICAL RESISTANCE OF THE ATMOSPHERE

The electrical resistance of a vertical column of unit cross-section in the atmosphere is a convenient concept for use when considering some aspects of atmospheric electricity. For example, the Earth and the high atmosphere may be regarded, for some purposes, as two conductors of negligible resistance which constitute a spherical condenser, the outer element of which has a potential V relative to the inner element. Then if r is the columnar resistance between the elements of this condenser, the electrical conduction-current density, i, through the column at a given place is V/r. At a place situated on a high plateau, r is doubtless generally less and i consequently greater than for a place at sea-level. This effect would be large if most of the columnar resistance were offered by the lower few km of the column, but would be small if the upper part provided most of the resistance. If r depends upon latitude, then i should vary with latitude. Furthermore, since at the surface the current-density is also equal to the product of the potential-gradient, E, and the total conductivity, λ, it follows that $V/r = \lambda E$, provided i is approximately constant throughout the column. For a case where V and λ are constant while r varies, say with latitude, E should vary inversely as r. This is an analogue of what appears to be an actual set of circumstances over the ocean.

In order to obtain an estimate of the value of r from the surface up to a certain height the reciprocals of values of air-conductivity, or the values of air-resistivity, are integrated from the surface up to that altitude. The values of r obtained in this way from values of conductivity registered on the flight of *Explorer II* may be read from the graph in Figure 10 by referring to the scale at the top of the Figure. The values of conductivity used here for the region below 600 meters were obtained by interpolating between the values registered at that level on this flight and the average value observed at sea-level over the oceans. This probably yields as representative an estimate of the columnar resistance as it is possible to obtain with data at present available. According to this estimate that resistance, from sea-level to an altitude of 18 km, is about 10^{21} ohms but most of this is offered by the lower part of the column, the upper eight km contributing only five per cent of the total whereas the lower two km contribute 50 per cent.

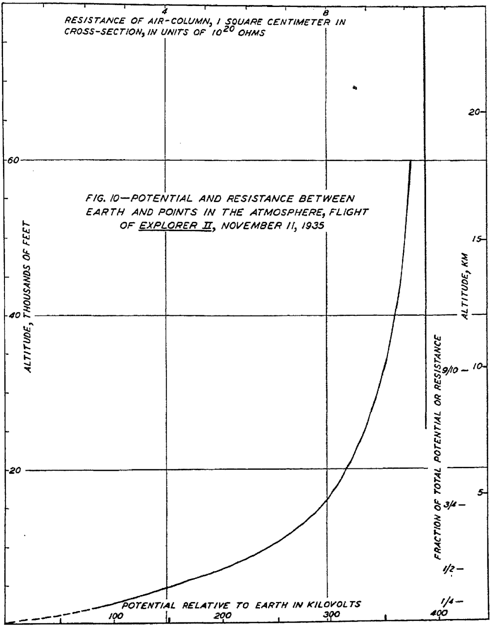


FIG. 10.—Potential and resistance between Earth and points in the atmosphere, flight of *Explorer II*, November 11, 1935.

Estimates of the columnar resistance up to altitudes considerably greater than 18 km may be based upon the observed values of cosmic-radiation intensity, and the trend indicated for that radiation at altitudes not yet explored, provided it is permissible to assume that the content of nuclei is generally negligible there. Although evidence unfavorable to this assumption was mentioned in the previous section, yet such estimates probably establish a lower limit and serve as a sort of "base-line" from which one may survey other features in the electrically unexplored region which extends from an altitude of 22 to about 50 or 60 km in the atmosphere.

According to such estimates the total resistance up to the ionosphere, where the ionization is known to be enormous, would not exceed by more than ten per cent that for a column up to 18 km. However, if an ion-diminishing constituent such as the nuclei of condensation is generally present and widely distributed there, the total columnar resistance would of course exceed these estimates. In case the conductivity everywhere in this region has the relatively low value registered at about 22 km, the total resistance would be about 50 per cent greater than that up to 18 km. This seems too large in view of the low values of current-density, observed at several places, where pollution that is apparently introduced locally has doubtless increased the resistance of the lower atmosphere and thereby decreased the current. If the resistance at places without abnormal pollution were as much as 50 per cent greater than that indicated in Figure 10, then at the places where the small currents are observed, the required vertical distribution of pollution would appear to be an unlikely one.

If the Earth and ionosphere may be regarded as a spherical condenser, then the average columnar resistance at different places should be in approximately the inverse ratio of the average air-earth current for the respective places. By that criterion the columnar resistance at some places on land near large cities, for example, in the suburbs of Washington and at the Kew Observatory near London, may be from two to five times the value over the oceans. On account of the difference in the vertical distribution of cosmic radiation (illustrated in Fig. 2) the resistance at the equator is estimated to be about 15 to 20 per cent greater than in middle latitudes. This is of the right sign and magnitude to account for the lower values of potential-gradient observed near the equator over the oceans.

IV. THE ELECTRIC FIELD OF THE ATMOSPHERE

If a long thin wire is stretched horizontally between insulating supports at a height of one meter from the surface of an extensive level area and if at the center of this span there is attached to the wire a device (collector) which quickly brings the wire into electrical equilibrium with the adjacent air, then the wire generally becomes charged to a potential of roughly 100 volts greater than that of the Earth during fair weather, with rare exceptions which are of short duration. This is one way of obtaining a measure of the potential-gradient, or field-strength, expressed in volts per meter.

(1) GENERAL ASPECTS

The potential-gradient varies considerably from place to place over land but numerous measurements made over the oceans, chiefly during cruises of the *Carnegie*, show no prominent dependence of the gradient upon position at sea. The average there is about 130 volts per meter. At some places on land an average considerably less than 100 is observed while at several places the average is more than 200 and at Kew Observatory, near London, it exceeds 300 volts per meter.

The magnitude of the gradient at a given place fluctuates with irregular short periods, as is illustrated in Figures 12 to 15, and with more regular longer periods, which often appear clearly only when averages are used as in Figures 11, 17, and 18. Although the average gradient varies somewhat from year to year [595, p. 381; 1305], from season to season, and from hour to hour during the day, yet records which at some places now extend over many years show no general tendency for the gradient either to increase or to decrease in the long run. Thus the changes consist in oscillations about a mean value.

Inquiry as to the origin of the Earth's average electric field leads to the conception of a supply-current, a current which somewhere must flow in a direction opposite to the electric conduction-current and supply negative charge to the Earth at a rate sufficient, on the average, to replenish that lost by electric conduction, or other possible processes, through the atmosphere. When the supply-current varies, there will result a change in the charge of the Earth and consequently also of the potential-gradient provided other factors have not varied in such a way as to annul or mask such an effect. Evidence of variations in the gradient which may reflect variations in the supply-current is sought because one may expect in that way to obtain a better conception of the character of the supply-current and clues as to the nature of the mechanism which maintains that current.

It is helpful when considering some of the broad aspects of the electrical field to regard the Earth as a perfect sphere of radius, R, which offers negligible resistance to the conduction of electricity. For such a sphere when charged with Q ESU of electricity, the field-strength everywhere at the surface would be given by Q/R^2 electrostatic volts/cm or 30,000 Q/R^2 volts/meter. When the potential-gradient, which is the negative of the field-strength, is 100 volts per meter, Q would be 1.35×10^{15} ESU or 450,000 coulombs of negative electricity. For such a model the potential-gradient would decrease so little with distance from the Earth that at any altitude accessible for measurement, the decrease could not be detected. For example, at an elevation of 100 km the gradient would be only three per cent less than at the surface.

(2) THE POTENTIAL-GRADIENT IN THE FREE ATMOSPHERE

However, observation shows that in general the gradient does decrease with altitude. This is attributable to the fact that the conductivity increases with altitude. Imagine two horizontal strata of air, the upper conducting better than the lower. If initially the potential-gradient along the perpendicular to the boundary is positive and of the same magnitude in both strata, then in the upper stratum positive ions would flow toward the boundary faster than they are removed in the lower stratum and negative ions would be moved upward away from the boundary faster than they are supplied from the lower stratum. An excess of positive over negative ions, or a positive space-charge, would thus be established in the region of the boundary. If world-wide in distribution, this positive space-charge would then in effect annul some of the negative charge on the Earth in so far as concerns ions in the upper stratum. Thus the gradient and the flow of ions in the upper stratum are reduced, the process continuing until the current-density is the same in both strata. In the equilibrium-state the space-charge density, ρ, no longer changes with time; that is, $d\rho/dt = 0$ and therefore the conduction-current, i_e, does not change with altitude so that $di_e/dz = 0$ if electrical convection is negligible. Therefore E varies inversely as λ, or $\lambda E = i_e$, a constant.

Schweidler [511, p. 340] summarizes the observations of gradient at altitudes up to nine km as in Table 4.

TABLE 4.—*Potential-gradient at various altitudes, after Schweidler*

Altitude, km	0	0.5	1.5	3	6	9
Gradient, volts/meter	130	50	30	20	10	5

The values of Table 4 satisfy the following empirical equation

$$E = 90e^{-3.5z} + 40e^{-0.23z}$$

where E is in volts per meter and z is altitude in kilometers. This is convenient for calculating quantities which may be derived from E. Thus the potential of a point at an altitude, h, may be obtained by integrating E from $z = 0$ to $z = h$. In this way one finds that a point nine km above the Earth is about 178 kv higher potential than the Earth, and at very great altitudes the potential is apparently 200 kv. These estimates are only about half those based on the observed conductivity and conduction-current, shown in Figure 10.

With the aid of this empirical equation the variation of E with altitude may be readily compared with that observed for conductivity, provided the conduction-current is independent of altitude. Although such a comparison is in the main consistent with the explanation, indicated above, for the decrease of gradient with altitude, yet there are some quantitative discrepancies which require further investigation. Simultaneous measurements of gradient and conductivity have been made on only a few balloon-flights (Gerdien, Wigand). Wigand concluded from his observations which extended over a considerably greater range in altitude than those of Gerdien, that the product λE decreases somewhat with altitude. Comparison of the means from all observations shows an increase of λE with altitude. Although the observations do not support the usual assumption, namely, that λE on the average is independent of altitude in the troposphere yet the data are probably not to be regarded as an adequate basis for questioning either that assumption or the explanation indicated here for the decrease of gradient with altitude in most of the troposphere and in the lower stratosphere.

The electrode-effect, already alluded to at several places in this discussion, is in part characterized by a depletion in the concentration of negative ions in the air near the surface, when the gradient is positive. The air in this stratum, therefore, has a net positive charge, which if world-wide in extent decreases the gradient at points above the charged stratum. The direct influence of this, however, is effectually included in the discussion of the dependence of the vertical distribution of E upon that of λ. Theoretical investigations of this effect in the atmosphere have been published by Schweidler, Behacker, Swann, Scholz [673]. Those of Schweidler [511, p. 340] and Scholz considered the especially important case of a non-turbulent atmosphere containing an abundance of nuclei uniformly distributed. For such conditions the electrode-effect is apparently appreciable in a stratum which extends only a few meters from the Earth. Turbulence, as well as some other air-movements, modify this effect. The observation that positive conductivity is greater than negative conductivity at most places at the surface, while the inverse holds in the free atmosphere, is doubtless evidence of this electrode-effect. The ratio of the components of the conductivity, that is, λ_1/λ_2, varies with the gradient when circumstances are not too complex—as is to be seen by comparing the lower graph of Figure 8 with the graphs in Figure 11.

The explanation of the decrease of gradient with altitude must be modified when electricity is also transported by other means than electrical conduction. The term electric convection will be used to comprehend a variety of such processes. These generally involve the motion of masses of electrically charged air or the fall of charged particles or of raindrops, etc. If i_c is the electric convection-current density, then, any lateral divergence being neglected in i_c and i_e

$$d\rho/dt = di_c/dz + di_e/dz$$

Since the space-charge density cannot increase indefinitely, when other factors are constant, it must on the average approach some constant value for which $d\rho/dt \doteq 0$. In this case $\lambda E \doteq (i_0 - i_c)$, where i_0 is independent of altitude and may have the value of the conduction-current at some level in the atmosphere where the convection-current vanishes. In any region where i_c does not vary with altitude, E will vary inversely as λ but when i_c varies with altitude the relation between E and λ may be appreciably modified. This may be a factor which contributes even during fair weather to the marked erratic departures, in the lower km of the atmosphere, from the rather regular decrease in E generally found at higher levels.

(3) VARIATIONS IN GRADIENT AT THE SURFACE

At some level in the atmosphere, doubtless below the ionosphere, the conductivity is so great that the region above that level may doubtless be regarded as a perfect conductor in which there is no appreciable potential-gradient. This region is then at a uniform potential doubtless of several 100,000 volts greater than that of the Earth (see Fig. 10). This highly conducting region of the atmosphere together with the Earth forms a sort of spherical condenser which on account of the conductivity of the air has a "leakage" resistance, r, in a column of unit cross-section. If the potential-difference between the two elements is V, then the "leakage" current-density is V/r which is equal to the conduction-current density, λE.

Then $V/r = \lambda E$. This relation and the conception upon which it is based aid in the consideration of some of the variations in E at the Earth's surface. Thus, for example, if values of E are observed at the surface, at two places which are at different altitudes above sea-level, since r would generally tend to be less for the place of higher elevation, E would be greater at the higher point if in a very shallow stratum near the surface λ is the same at the two places. But λ at the surface generally tends to be greater at the higher elevation so that values of E at the surface on that account tend to be independent of the elevation of the land, except when the observations are made on prominences.

The relation, $V/r = \lambda E$, is definitely not applicable in cases where either di_e/dz or $d\rho/dt$ is not equal to zero. Thus, for example, if electricity is transported by processes other than electrical conduction, or if the net charge in any part of the column is varying, or if electrical separation is taking place there, E may vary in a manner dependent upon the variation with altitude in the conduction-current, or the variation with time of the space-charge, even though V, r, and λ are constant. The latter may be regarded as one of the several categories in which variations of potential-gradient, either temporal or positional, may be placed.

Although the variations are often complex, examples may be cited of several simple types which may be defined with reference to the relation, $V/r = \lambda E$, as follows: Type (*a*) in which $E \propto 1/r$, while λ and V are approximately constant; type (*b*) in which $E \propto V$, while λ and r are constant; type (*c*) in which $E \propto 1/\lambda$, while V and r are constant; and type (*d*) in which E is independent of V, λ, and r, that is, cases for which either $d\rho/dt$ or di_e/dz is not equal to zero throughout the column, so that E depends primarily upon these factors.

Variations of type (*a*).—It was pointed out by Mauchly [608, pp. 387–424] that the potential-gradient in low latitudes, as indicated by observations made at sea during cruises of the *Carnegie*, is about ten per cent less than in high latitudes. This difference appears to be more nearly 20 per cent when allowance is made for an apparent progressive change from year to year during the period when these observations were made. According to the conception of the Earth and atmosphere as a spherical condenser, a latitude-effect of this sign and magnitude is to be expected if there is an inverse latitude-effect in the columnar resistance, r, and if λ at the surface is independent of latitude. That r is greater near the equator than in high latitudes is to be inferred from the difference in the vertical distribution of cosmic-radiation intensity at the different latitudes (see Fig. 2) and it is found by calculations, based on cosmic-radiation data, that that difference amounts to nearly 20 per cent—as in those by Gish and Sherman in discussing latitude-effect in electrical resistance of a column of atmosphere ["Trans. Amer. Geophys. Union," 19th Annual Meeting, 1938]. Similar calculations also indicate that although the intensity of cosmic radiation is about 12 per cent less near the equator than in high temperate latitudes, yet on account of a compensating effect of temperature, λ is nearly independent of latitude. This is also supported by the observations of λ made at sea.

Variations of type (*b*).—If the potential of the high atmosphere is changed without a compensating change in r or λ, then the gradient at the Earth's surface may be expected to show a change, corresponding to that in V, everywhere on the Earth. That the diurnal variation in potential-gradient at sea (Fig. 11) is almost entirely of that character is evidenced by the fact, first pointed out by Mauchly [608], that this variation follows a universal time-schedule. The diurnal variation in the polar regions and at places on land, where disturbing factors are negligible, is also of this type. Perhaps the annual variation partakes somewhat of this character but other factors certainly play a prominent rôle in determining the magnitude and character of that feature at most places on land. Whether there are variations of this type having periods greater than a year or less than a day cannot be decided on the data thus far available. Variations of this type, implying as they do a variation in V, are world-wide phenomena and doubtless have a significant bearing on the fundamental problem of atmospheric electricity, namely, that of the nature and origin of the supply-current.

Variations of type (*c*).—These may be temporary changes which run their course in a few minutes, or they may be variations of long duration or may consist in permanent differences between places. That the diurnal variation at the Huancayo Magnetic Observatory, on a typical day of the dry season, is chiefly of this type is apparent from the reciprocal relation between the gradient and conductivity shown in Figure 14. This type of variation in gradient is controlled by the several circumstances which have already been seen to control the conductivity, but changes of longer duration are generally modified in character and diminished in

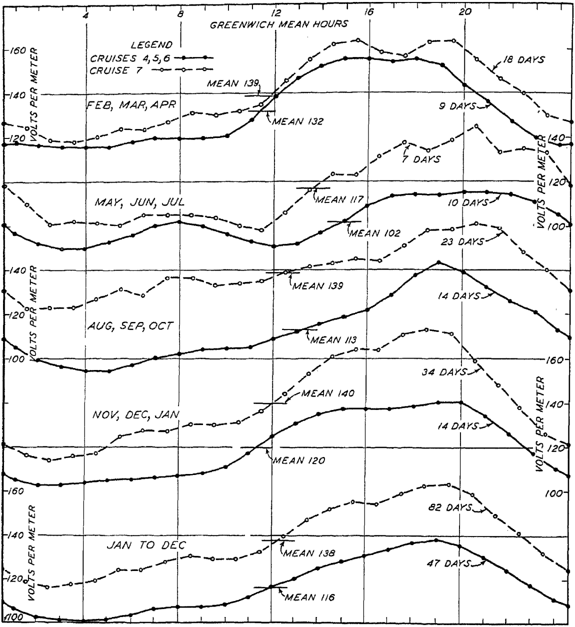


FIG. 11.—Mean diurnal variation of potential-gradient for three-month periods from observations on board the *Carnegie*, 1915–21, and 1928–29.

amplitude by changes in r which are likely to be associated with those in λ, because the latter are then likely to extend to a considerable altitude.

Variations of type (d).—These are very conspicuous during stormy weather, when intense space-charges, of irregular and varying distribution, are established by one or more of several possible mechanisms which are most highly developed at times of storm. The variations in gradient at such times may be very great (see Chapter XII) and at times they alternate between positive and negative extremes in a few minutes. Variations of that character are shown in Figures 13 and 15, except when they were too great or varied too rapidly to be recorded.

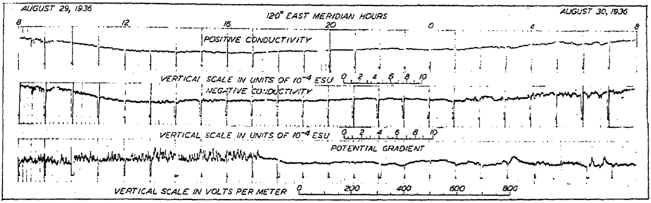


FIG. 12.—Electrograms, Watheroo Magnetic Observatory, "quiet" day.

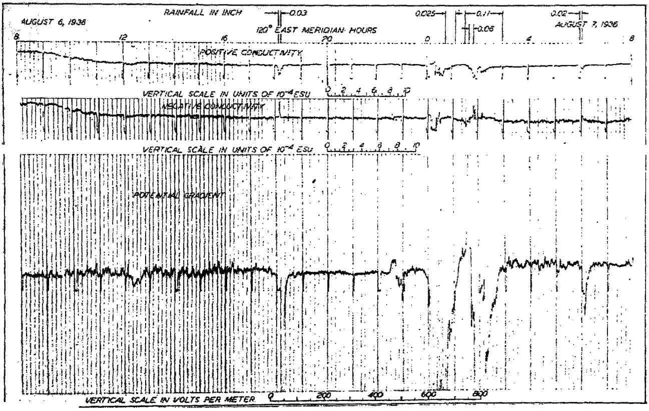


FIG. 13.—Electrograms, Watheroo Magnetic Observatory, with periods of light rain.

Variations of type (*d*) also occur in fair weather. Irregular variations of potential-gradient which are typical of daytime (8^h to 17^h) at Watheroo

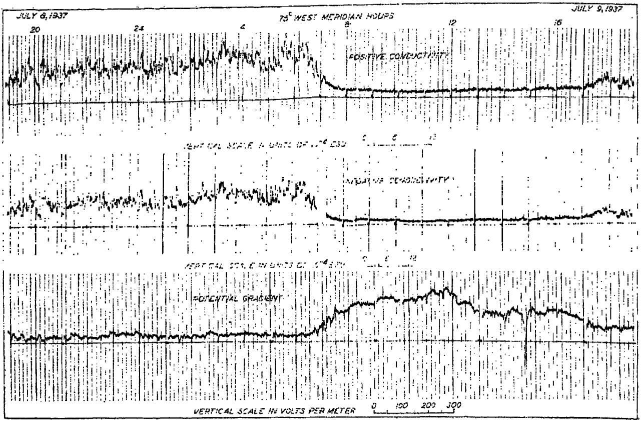


FIG. 14.—Electrograms, Huancayo Magnetic Observatory, "quiet" day during dry season.

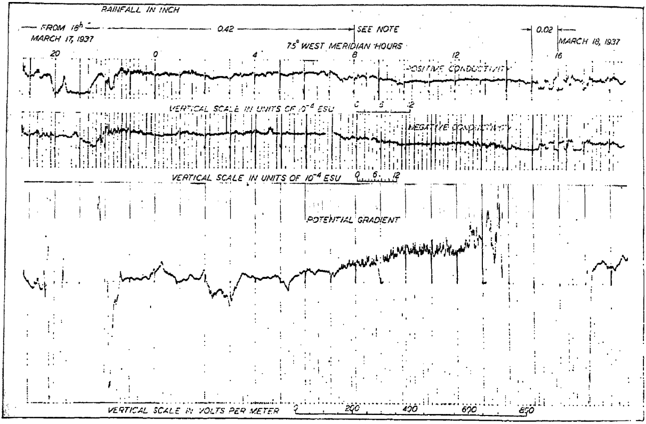


FIG. 15.—Electrograms, Huancayo Magnetic Observatory, rainy day (Note: Clearing in morning after $10^h.5$; early afternoon March 18, increasing cloudiness, distant rain, and thunder to southwest at 14^h).

are shown in Figures 12 and 13—where it is also seen that there are no comparable changes in conductivity. These are closely associated with the velocity and turbulence of the wind which suggests that electric charges are generated and introduced into the air by the action of the wind on the fine dry sand which covers much of the area around that Observatory. Such effects are also observed at other places when wind of sufficient velocity blows over areas of dry sand [498, pp. 142–146].

An interesting variation of this type is shown on the lower gram of Figure 14 between 14^h40^m and 14^h50^m. This is the typical electrical effect of whirlwinds, or dust-whirls, which are common on mid-afternoons of the dry season at Huancayo. It shows quite clearly that negative charge is introduced into the air by such whirls. In the active portion of dust-storms the gradient at the surface is generally negative and approaches the magnitude of that near a thunder-storm. A negative charge is also introduced into the air by drifting snow and Kähler reports the curious observation that at a position, several km to the leeward of a field of wheat in bloom, the gradient was negative for hours at a time when the wind-velocity was suitable. There is little definite evidence that a positive charge is introduced into the air by natural processes, except those which bring about the separation of charge in the storm-cloud.

Negative gradients are sometimes reported at times of clear weather. Although this is doubtless evidence that negative charge is being supplied at a certain rate, yet it is not possible with the information at present available to assign the source of supply in some such cases. However, that source may be some tens of km away. Although a charge which differs from the normal equilibrium-charge of the air is diminished to one per cent of its initial density in a time, T, given by $T = 0.366/\lambda$, yet T may be large enough (30 minutes for $\lambda = 2 \times 10^{-4}$ ESU) at some places, especially when the conductivity is small, so that even for moderate wind-velocities a source several tens of km away may supply charge at a rate sufficient to account for these observations of negative gradient in fair weather.

All the variations in gradient of type (*d*) which have been cited are such as require that the space-charge be present in the air over restricted areas, namely, that it occur in the form of clouds or of streams which are of relatively small lateral extent compared with that of the whole Earth. If present everywhere in the same amount over each unit-area of the Earth, the effect on the gradient at the surface would be quite small and would be nil if the distribution were uniform in strata that are concentric with the surface of a perfectly spherical Earth, even though the density of space-charge should vary considerably from one stratum to another.

However, space-charge in such a general and symmetrical distribution may be indirectly involved in typical variations of the gradient. This would come about through air-movements or mixing which tend to transport charge from regions of plenty to regions of scarcity. The electric current which is produced in this way comprises part of the total air-earth current. This contribution cannot extend from the surface to the "top" of the atmosphere. In the region where this process of electrical transfer is effective the gradient becomes adjusted in such a way that the sum of the conduction-current and the convection-current there is equal to the current at some other altitude in the vertical column where convection-currents are lacking. If there are convection-currents in the air near the surface, then the gradient will change as the convection-current changes. It will be greater than normal if the convection-current is directed upward and smaller when the latter is directed downward in a limited portion of a vertical column of the atmosphere.

(4) THE ELECTRIC CHARGE OF THE AIR

The space-charge, ρ, or the density of the net electric charge of the air, has been mentioned at various points in this chapter. Relations between small and large ions were developed in a form which requires (*a*) that the density of space-charge is approximately independent of time ($d\rho/dt \doteq 0$) and (*b*) that ρ is either approximately independent of altitude or else varies with altitude in a peculiar manner which will not be specified here. The assumption that the conduction-current is independent of altitude also implies that $d\rho/dt \doteq 0$ and (*c*) that ρ is proportional to the rate of change of air-resistivity, $1/\lambda$, with altitude, or expressed in symbolic form, $\rho \propto -i[d(1/\lambda)/dz]$. Condition (*b*) is not at all like condition (*c*).

The extent to which ρ varied with time at Washington on a day which was undisturbed by storm is indicated in the gram at the bottom of Figure 16, which is constructed from results obtained by Gish and Sherman during a short period of registration. The space-charge was registered continuously during alternate hours, the "zero" of the measuring equipment being registered during the intervening hours. The ordinate, measured from the "zero"-trace, is proportional to the space-charge and may be expressed in electronic charges per cc (e/cc) with the aid of the scale to the left of the gram. The space-charge during all hours of registration shown here was positive but negative space-charge was registered for short intervals on some days of the month during which these registrations were continued. On this day the average space-charge was less than 400 e/cc. The lowest value, less than 100 e/cc, was registered shortly after 22^h and the highest, approximately 600 e/cc, at about 0^h30^m. There are conspicuous variations of duration from five to ten minutes, for several of which $d\rho/dt$ is about 0.3 e/cc sec. The amplitude shown on the trace for a variation of duration five minutes, or less, is definitely too small because the time-constant, or relaxation-time, of the

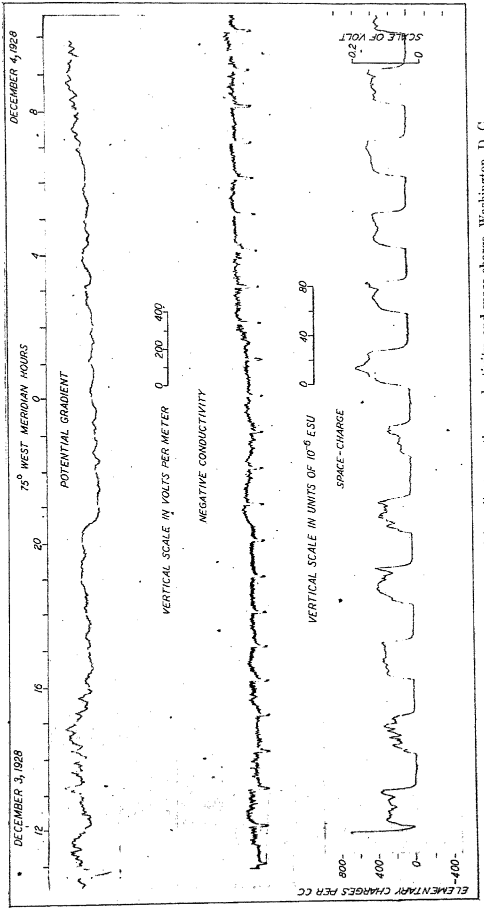


FIG. 16.—Records of atmospheric potential-gradient, negative conductivity, and space-charge, Washington, D. C.

recording equipment is quite large as can be seen from the rate of approach to the zero-trace. This record therefore indicates that even on a day that is relatively free from electrical disturbance $d\rho/dt$ often differs from zero by more than 0.3 e/cc sec which implies an appreciable departure from ionic equilibrium especially at a place where the rate of small-ion formation is small.

Such values of $d\rho/dt$ are however much less disturbing for the assumption that the air-earth current is independent of altitude, unless these variations should extend to considerable altitudes, but there is considerable evidence against such a possibility. For example, the records of potential-gradient and of negative conductivity, also shown in Figure 16, which were made simultaneously with those of space-charge, but at a site distant about 50 meters and at an elevation about ten meters higher, are not closely correlated with those of space-charge, which apparently indicates the local character of the short-period variations in space-charge.

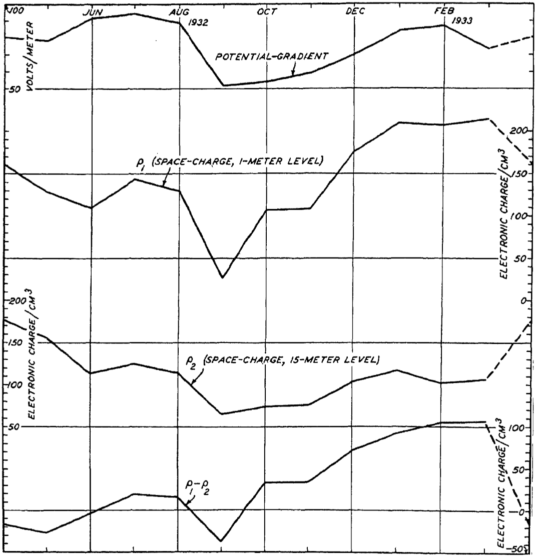


FIG. 17.—Potential-gradient and space-charge, Stanford, California, April, 1932, to March, 1933.

The character of the annual, as well as that of the diurnal, variation of space-charge apparently varies considerably from place to place. Observations by direct methods have been made in Germany (Daunderer), Sweden (Norinder), Germany (Kähler), Russia (Obolensky), and in the United States (Brown, also by Gish and Sherman for a short period). Results obtained by Brown [599-*A*] with two recorders, one taking the sample of air from a level of one meter, the other from a level of 15 meters, are shown in Figures 17 and 18. From Figure 18 it is to be seen that in the average diurnal variation at Stanford, California, where Brown's observations were made, $d\rho/dt$ is so small that it may without error be regarded as zero in cases where that is usually done. The range of variation, both annual and diurnal, is definitely less at the 15-meter level than at one meter above ground-level. This is in accord with other evidence—one phase of which was illustrated by Figure 16—which indicates that the magnitude of the space-charge and the character of its variations are

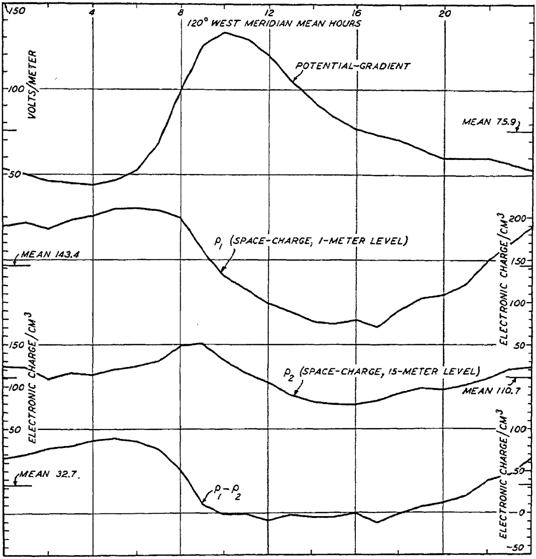


FIG. 18.—Diurnal variation in potential-gradient and space-charge, Stanford, California, April, 1932, to March, 1933.

largely local phenomena, that in fair weather the space-charge tends to be somewhat concentrated near the surface, and that important sources of the variations are located at or near the surface. The mean value for the year 1933, at the one-meter level (143 *e*/cc), is greater than that at the 15-meter level (111 *e*/cc). These values are numerically less than values reported by several investigators. Norinder found negative values in the average both for summer and for winter. The extremely large average values of 1,260 *e*/cc for summer and −1,000 *e*/cc for winter are reported by Daunderer. Obolensky found negative space-charge in the average for August and September only. [For a further description of methods and of results see reference 489.]

The variation of space-charge with altitude in the free atmosphere is calculated from the observed variation of potential-gradient with altitude. Such calculations depend upon Poisson's theorem which is expressed by the equation

$$\partial E_x/\partial x + \partial E_y/\partial y + \partial E_z/\partial z = -4\pi\rho$$

where E_x, E_y, and E_z are components of the gradient along the x, y, and z axes of reference, respectively. It is however assumed that the first two terms are zero, an assumption which is likely to be a close approximation at higher levels during fair weather. However, near the surface, this obviously does not apply except when dealing with averages taken over a period of time long enough so that the contributions from the lateral components, which may be negative as well as positive, total zero.

One may thus readily derive the space-charge from the empirical expression for the variation of gradient with altitude by differentiating with respect to the altitude, z. The result is

$$\rho = 17.5e^{-3.5z} + 0.52e^{-0.23z}$$

where z is in km and ρ is in *e*/cc. This gives a value for the surface of 18 *e*/cc, which is considerably smaller than the average reported by all other investigators except Obolensky who gives an annual mean of 6.9 *e*/cc. The results obtained for the lower altitudes, from this empirical relation, are not so significant as those for higher levels because the gradient in the lower km varies erratically from various causes. Brown's results indicate that near the surface the rate of decrease with altitude is 1.5 per cent per meter, or about four times the percentile rate of change that is given by the empirical equation. Other less direct evidence also suggests an abrupt decrease near the surface.

Above one km the change of ρ with altitude is determined by the second term of the equation. This may be regarded as more representative of actual conditions in fair weather than is the relation for lower levels. One reason for this conclusion is that the observations of gradient, upon which the empirical relation depends, are much more consistent here than at low levels. Another is that such a trend is verified quantitatively, for altitudes greater than seven km, by the measurements of air-conductivity made on the flight of the balloon *Explorer II* according to the following considerations.

If the vertical conduction-current is independent of altitude, then $\lambda E = i$, where i is regarded as a constant. It follows that

$$dE/dz = -(E/\lambda)(d\lambda/dz) = -(i/\lambda^2)(d\lambda/dz) = i[d(1/\lambda)/dz],$$

and for $(dE/dz) = -4\pi\rho$, one obtains an expression for ρ in terms of $1/\lambda$, or the air-resistivity, namely,

$$\rho = -(i/4\pi)[d(1/\lambda)/dz]$$

Values of ρ calculated in this way are compared with those obtained from the empirical equation for the variation of E with altitude in Table 5.

TABLE 5.—*Space-charge in the free atmosphere*

Altitude, km	0.0	0.2	0.6	1.0	1.5	3.0	5.0	7.0	9.0	12	15	18
Space-charge, *e*/cc:												
(*a*) From observations of potential-gradient......	18	9.2	2.6	0.94	0.46	0.26	0.17	0.10	0.06			
(*b*) From observations of air-conductivity........	..	...	(2.6)	2.2	1.8	0.89	0.38	0.12	0.07	0.04	0.016	0.011

Although the space-charge on the average is positive and decreases with altitude up to the 18-km level, yet variations from that trend are indicated by the values of both potential-gradient and conductivity. Thus by referring to Figure 9 it is to be seen that the conductivity decreases with altitude in some relatively short altitude-intervals below 18 km. This is probably to be regarded as evidence of a negative space-charge at some levels. The general decrease of conductivity from about 100×10^{-4} ESU at 18 km to 60×10^{-4} ESU at 22 km indicates that the average space-charge there was roughly -0.04 *e*/cc at the time and place of the flight on which the observations were made.

Although the data are too meager to determine the full significance of the features which have been pointed out, yet the following major aspects of the variation of space-charge with altitude seem to be definitely indicated: (*a*) The space-charge is generally positive; (*b*) it decreases with altitude, very rapidly near the surface and, at a height of one km, is perhaps only a few per cent of the value at the surface; (*c*) the average value and the magnitude of the variations during fair weather are so small, except within a few tenths of a km from the surface, that in various considerations, variations either with time or with altitude may be neglected.

V. THE ELECTRIC CURRENT IN THE ATMOSPHERE

An electric current in the atmosphere may arise from the movement of charge either in response to electrical forces or in response to mechanical forces. A current of the former origin has been designated an electric conduction-current, while one of the latter has been termed a convection-current. A current due to electric displacement is not considered here. Currents of that origin are of negligible significance for the main problems of atmospheric electricity.

(1) THE ELECTRIC CONDUCTION-CURRENT

The factors which immediately determine the electric conduction-current, namely, the conductivity and the potential-gradient, have been reviewed at some length in sections III and IV of this Chapter. The characteristics of the conduction-current may be readily inferred from the characteristics of those factors.

Because circumstances which affect the factors λ and E are generally simpler over the oceans than at most places on land, where these factors have been observed, and because the measurements made at sea are for a much better distribution of positions, the values for the conduction-current, i_e, derived from these measurements are probably the best representation for the Earth as a whole that is at present available. The conduction-current has an average density at sea of about 11×10^{-7} ESU/cm^2 or 3.7×10^{-16} amp/cm^2 and flows from air to Earth except on rare occasions. For the whole Earth this would amount to a total current of 1,800 amp.

Whether the average current for the Earth as a whole varies from year to year cannot be definitely determined from information now at hand, but the observations made on the *Carnegie* at sea indicate that it is relatively constant. Although the averages of conductivity and of gradient varied from cruise to cruise their products differed by only a few per cent.

A seasonal variation is found at stations on land but this differs so much from place to place, and observations are available for so few places, that a world-wide seasonal trend is not definitely established by those data nor is it indicated by the data obtained at sea. It has been surmised that the conduction-current generally tends to be greatest at time of northern winter in all parts of the Earth. If this should be established, it would constitute an important clue to the source of the supply-current.

The most interesting variation of the conduction-current, which is doubtless also a feature of the supply-current, is the diurnal variation. The character of this is adequately shown by the diurnal variation of potential-gradient which is most clearly revealed by the observations made at sea. It has already been seen that the diurnal variation in conductivity at sea is very small so that the product λE varies chiefly with E. From the two graphs at the bottom of Figure 11 it is to be inferred that in the average i_e varies from a minimum at 2^h to 4^h GMT to a maximum at 19^h to 20^h GMT, the total range being about 40 per cent of the mean. The character of the diurnal variation apparently varies somewhat with season. The amplitude may also undergo a seasonal change but one would like to see more evidence in support of this.

There can be scarcely a doubt that the diurnal variation of i_e at sea, progressing as it does on universal time instead of local time, is a manifestation of the supply-current, which is the chief unknown and the primary element in the general atmospheric-electric phenomena of fair weather. It is for this reason that variations in i_e, whether of diurnal or other period, which follow a universal time-schedule are of special interest and require further investigation.

That the vertical electric conduction-current is approximately independent of altitude is indirectly indicated. However, the simultaneous observations of potential-gradient and conductivity which are required directly to test this have been made on only a few occasions. Gerdien concluded that i_e is independent of altitude but observations made later by Wigand on three balloon-flights—one of which reached an altitude of nine km—led him to conclude that i_e probably decreases with altitude. However, one hesitates to accept this conclusion, because the data were too meager to enable him to eliminate other possible interpretations. If such a conclusion should be supported by future observations and should be shown to be general, then it would follow that the total electric current in the atmosphere contains a component which is of the character of a convection-current and that that component increases algebraically with altitude. In that case the total electric conduction-current for the whole Earth would not equal the supply-current. Hence other processes of transporting electricity would require consideration.

(2) ELECTRIC CONVECTION-CURRENT IN THE ATMOSPHERE

Although electricity is doubtless transported by the movement of air which has a net electric charge, as was indicated in the general survey, yet it is not proved that the air-earth current in general contains an important component of such origin. There are, however, several reasons for regarding this as an open question.

One of these is that the current collected by an insulated plate—that is, set flush with the surface of the Earth (the so-called direct method)—is in the average less than the product of the observed values of λ and E. Since the plate may receive charges by convection as well as by conduction, the lower values obtained by the "direct method" may be taken as evidence that, in addition to the positive electricity carried to the plate by electrical conduction, negative electricity is also brought to it by some other processes. Or the plate may receive charge by electrical conduction only and, since measurements of λ and E are generally made at a height of 0.5 meter or more from the surface, it would follow that λE increases with altitude very near the surface. This interpretation would also imply that, in the air near the surface, negative electricity is moved toward the Earth, but not to it, or that positive electricity is moved away by some mechanical process. The latter statement rests on the assumption that the net current-density, i, is equal to the convection-current density, i_c, plus i_e, and that i is independent of altitude.

A mechanical process which is capable of effecting a negative convection-current nearly everywhere on the Earth during fair weather depends upon the mixing action of wind, or eddy-diffusion, and upon the existence of a positive space-charge density which decreases with altitude. The convection-current arising in this way is given by the expression, $i_c = A d\rho/dz$. The sign of i_c is negative when negative electricity is moved toward the Earth; $d\rho/dz$ is the rate of change of space-charge with altitude and A is the coefficient of eddy-diffusion. According to Wilhelm Schmidt, near the Earth, A depends upon altitude, namely, $A = A_1 z^{\frac{4}{3}}$ where A_1 is the value of A at $z = 1$. Since ρ decreases with altitude, this convection-current is negative with respect to the conduction-current and vanishes at the Earth's surface. If the dependence of ρ upon altitude is approximately expressed by the empirical equation given in the discussion of space-charge, then i_c would be of greatest magnitude at an altitude of about 250 meters from the surface and would decrease rapidly at higher altitudes.

Magnitude of the conduction-current would vary in the same way as the convection-current if the net current were constant, that is, if $(i_c + i_e) = i =$ constant. Hence, this mechanism could account for decrease of i_e with altitude, indicated by Wigand's observations, and also for smaller values observed immediately at the Earth's surface by the direct method, provided the space-charge were very great near the surface and decreased rapidly with altitude. However, calculations, based on the observations of Brown (Figs. 17 and 18) and using for A_1 at one meter the value 840 cm^2/sec, indicate that the average convection-current near Palo Alto, California, at one meter above the surface, is not more than one per cent of the average conduction-current at sea, although the rate of change of ρ with altitude at that place is about 38 times the maximum indicated by observations of potential-gradient in the free atmosphere. Furthermore, the greatest value of i_c is located at an average altitude of about 50 meters and amounts to only ten per cent of the average conduction-current, provided that—at least up to a height of 50 meters—the space-charge decreases exponentially with altitude and the coefficient of eddy-diffusion increases as the $\frac{6}{7}$ power of the altitude. Although F. J. W. Whipple, R. E. Watson, H. Grieger, and, recently, J. J. Nolan and P. J. Nolan have considered this problem, it yet remains to be determined whether a convection-current, of sufficient magnitude to account for the disparity indicated above, is a general feature of the atmosphere in fair weather. Observations designed to determine whether electrical convection plays an appreciable rôle at sea would be especially helpful for determining the extent to which the measures of the electric conduction-current now available represent the magnitude of the supply-current and the manner in which this changes with time.

(3) THE SUPPLY-CURRENT

The observations which provide a measure of the conduction-current density show definitely that negative electricity is supplied to the Earth and positive electricity to the higher strata of the atmosphere by some process, the effectiveness of which neither increases nor decreases over a long period of years, but which may fluctuate somewhat from year to year and from season to season in a manner not yet definitely determined, and which definitely varies in a fairly regular manner during the day, being least at 3^h to 4^h after Greenwich midnight and greatest about 16 hours later. This process is apparently not at play in any fair-weather area of the Earth, either at sea or on land. It seems to bear no prominent relation to the phenomena of terrestrial magnetism, of earth-currents, or of aurora, although it is surmised by some [L. A. Bauer, A. W. Lee, H. U. Sverdrup, J. Scholz, P. A. Sheppard] that variations in the potential-gradient are associated in a minor way with one or more of these other geophysical phenomena, and with sunspots [Bauer]. At the present time this can be regarded as only a surmise.

If the process which provides the supply-current is not located in areas of fair weather, one must then look in areas of storm for this process. The rate at which electric energy is developed there is certainly adequate. From data given in Chapter XII, it is estimated that altogether the thunder-storms in progress at any time on the whole Earth develop 2×10^9 kw of power, whereas that required to maintain the total fair-weather conduction-current (about 1,800 amp) between the high strata and the Earth (total resistance 200 ohms) is about 6×10^5 kw, or only 1/3,000 of the aggregate electric power of the storms. This seems to imply a surprisingly fine adjustment of the supply-process if it is closely related to the more active electrical mechanism of the storm.

Some support for the surmise that the supply-current is generated in areas of storm was noted by F. J. W. Whipple in data assembled by C. E. P. Brooks on the frequency of thunder-storms over the Earth. These data indicate that thunder-storms occur most frequently at about the same time of the Greenwich day that the potential-gradient (and hence the conduction-current) at sea is greatest, a correspondence which is well preserved throughout the day. If the thunder-storm is the seat of the supply-current, then a record of potential-gradient at a place relatively free from local influences, for example, at sea, may be regarded as an approximate record of the frequency of thunder-storms on the Earth and as such would doubtless have some value for the study of world meteorology.

Numerous other theories have been devised to account for the maintenance of the electric charge of the Earth. Apparently every known physical mechanism, and some others, have been invoked, but the "thunder-storm theory" alone survives, except for a few theories in which departures from classical physics have been seriously considered as necessary to account for observed facts of atmospheric electricity and terrestrial magnetism [W. F. G. Swann, E. Schweidler]. It will doubtless be necessary to resort to such theories if it is eventually found that the supply-current is not generated in areas of storm.

CHAPTER V

INSTRUMENTS USED IN OBSERVATIONS OF ATMOSPHERIC ELECTRICITY

O. W. TORRESON

Department of Terrestrial Magnetism, Carnegie Institution of Washington

I. INTRODUCTION

This Chapter is devoted to brief descriptions of instruments and apparatus used in observations on the electricity of the atmosphere. No attempt has been made to enumerate or discuss all the pieces of apparatus that have been devised and used for the purpose. On the contrary, most of those described have been chosen because they are familiar to the author through years of use while at the same time they are known to represent sound principles of design and construction for their respective purposes.

It has been the plan throughout the Chapter to show the extent to which different kinds of apparatus have common features, and the reader will become familiar with various items of equipment that are used over and over again. It is hoped that by showing the different applications of various pieces of equipment the reader will be led to some application of his own which may contribute to the solution of problems in his particular field of research.

Although it may be said that measurements in atmospheric electricity near the Earth's surface began about two hundred years ago with the memorable kite-experiments of Benjamin Franklin in the United States and the work of Lemonnier in France, it is only within the last fifty years that those measurements have been made which have given us our present comprehensive, though by no means complete, understanding of the subject. It was the presentation in 1895 by Sir J. J. Thomson of the ionic theory of the conduction of electricity through gases that brought about the introduction and development of instruments and methods of observation which are in use today. About that time Elster and Geitel made their extensive series of experiments on the loss of electricity by a charged body exposed to the air; their conclusions, together with those of many other investigators working then and later, have shown how air-molecules or clusters of air-molecules carry positive and negative charges, how these charges are gained and lost by the molecules, where the electricity comes from that the molecules acquire, and what relations exist between electrified air-molecules, electric current and potential in the atmosphere, electrified clouds and lightning, and electrified foreign matter in the air. Such matters as these have taken students of atmospheric electricity into the fields of radioactivity, cosmic radiation, meteorology, and atmospheric pollution.

From the foregoing statement it may be surmised that for the study of atmospheric electricity a number of different instruments and pieces of apparatus are required. Comprehensive treatment of the subject involves the use of two or three instruments for measuring potential-gradient, an apparatus consisting of two similarly constructed units for measuring positive and negative conductivity, an apparatus of two units for counting positive and negative molecular (or atomic) ions, and another for measuring the number of charged particles, positive and negative, many times as large as molecular ions, which are known as large ions. In recent years it has become recognized that measurements must also be made of the number of ions of mobility and size intermediate between the molecular, or small, ions and the large ions, and apparatus has had to be devised for that purpose.

Furthermore, the number of large ions in the atmosphere is related to the number of neutral particles which, acting as centers for condensation of moisture from the atmosphere, are known as condensation-nuclei. For the student of atmospheric electricity a condensation-nuclei counter provides much important information.

Other instruments include an ionization-apparatus for determining the rate of production of small (molecular) ions and equipment for measuring the space-charge of the atmosphere.

Measurements over many years have established quite definitely the magnitudes of the several atmospheric-electric elements. The potential-gradient in fair weather varies from a few volts per meter to a few hundred volts, and in bad weather from several hundred to many thousand volts per meter, near the Earth's surface. The conductivity of the atmosphere is extremely small or, conversely, the resistivity very great, the latter being of the order of 10^{16} ohms. There are in most places only a few hundred small ions of each sign in each cc of the atmosphere and, in the same volume, a few hundred intermediate ions, thousands of large ions, and tens of thousands of condensation-nuclei. Small ions are produced at the rate of ten pairs, more or less, in each cc every sec by cosmic rays and radiations from radioactive substances—alpha particles produce half of them, beta and gamma rays 30 to 40 per cent, and cosmic rays 10 to 20 per cent. With these magnitudes in mind of the quantities involved, some of the details of instruments and apparatus will be more readily appreciated.

II. POTENTIAL-GRADIENT APPARATUS

To determine the potential-gradient or intensity of the electric field of the Earth, it is customary to measure the potential-difference between two points in the air, one of which is vertically above the other. If the difference in potential is dV and the vertical distance between the two points is dh, the potential gradient is given by dV/dh. It is customary in "field-observations" to select some open, level site, well away from buildings and trees, and to take one of the points of measurement at the surface of the ground and the other one meter vertically above it. The observations then give directly the potential-gradient in volts per meter, representative of conditions in the first few meters above the ground at that particular locality.

The potential at the point in the air is determined by some form of "collector." Collectors consisting of sharp metallic points similar to the ends of lightning-rods were chiefly used in early observations in fair weather and are still used for observations during bad-weather periods. In present-day practice fair-weather measurements are nearly all made either by means of some adaptation of Lord Kelvin's water-dropper [583] or by means of radioactive collectors. A mechanical collector has, however, been used for extended observations at atmospheric-electric stations in Norway [576]. In the water-dropper method it is necessary to insulate a vessel of water, the water being permitted to run out in a small jet or spray from a tube projecting from the side of the vessel. Under the inductive action of the electric field on the droplets of the jet or spray, the insulated vessel assumes the potential of the air in the region of the droplets. If the insulated vessel is connected electrically to the insulated measuring-element of an electrometer, this, too, will acquire the potential of the air at the breaking droplets and will indicate the value of the potential. It is evident that the replenishment of water for the water-dropper collector for extended periods of observation may sometimes be a problem, as may also the matter of freezing of the water at stations where very cold weather is encountered. The water-dropper collector is, furthermore, large and cumbersome compared with the radioactive collector, as is also the mechanical collector, already mentioned, which requires a motor for operating it.

A radioactive collector usually consists of a short piece of metal rod or a small metal disk, coated with a thin layer of radioactive material (a few mg of thorium ionium nitrate salt, eight to ten per cent ionium) which is held in place and protected against weathering by a thin coating of a suitable lacquer or enamel that is baked on [571]. Such a collector will remain active for years unless weathering is excessive.

Mention has been made of the need for insulating the water-dropper collector. All collectors must be insulated from their supports as must the measuring elements of the electrometers. Good insulation is one of the most important factors in all atmospheric-electric measurements for, unless the insulation is adequate, the charges being measured leak away to ground wholly or partially, and in either case the observations are worthless. Long experience has shown that electrometers function well if the measuring-elements in them are supported in quartz or amber, or both, and that collectors operate well when supported in sulphur or amber or, among recently developed products, in ceresin wax. It is a matter of experience also that such insulating materials as rubber, bakelite, porcelain, and common glass do not provide adequate insulation for atmospheric-electric collecting- and measuring-systems.

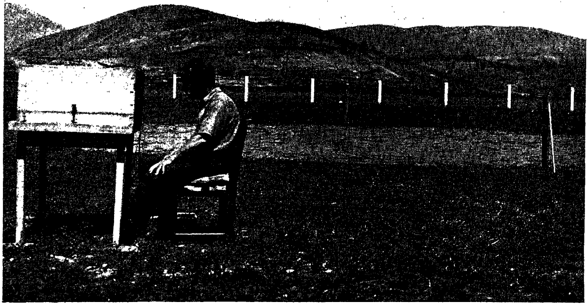


Fig. 1.—Potential-gradient field-station showing cleared circular area and posts for horizontal supporting-wire for collector.

To return now to the potential-gradient apparatus, the radioactive collector may conveniently be mounted by supporting it at the middle of a horizontal wire which is suitably insulated from its supporting posts. The posts, in order to reduce distortion of the equipotential surfaces to a negligible amount, must be ten times or more their own height away from the collector, so that a wire stretched between posts one meter high should be not less than 20 meters long. Further to minimize distortion of the field, the ground under the collector must be cleared of tall grasses and other protruding objects, as shown in Figure 1.

One of the most suitable and convenient electrometers for field-measurements is the Wulf type of bifilar electrometer [591], in which the mutual repulsion of two quartz fibers, made conducting by a metallic coating, is proportional to the difference of potential being measured between the collector and ground. Figure 2 shows such an electrometer; the fibers, not visible, are mounted vertically at the center of the electrometer-case, and their separation or deflection is noted against a scale in the eyepiece of the observing microscope. Such an electrometer is light and portable, may be adjusted over a considerable range of sensitivity, and maintains a high degree of constancy of calibration under ordinary handling. The fibers, it may be of interest to add, are supported at the top in amber and at the bottom are attached to a quartz bow. Installed in a shelter such as that shown at the left in Figure 1 and connected by a light wire to the collector-system, the electrometer provides a most satisfactory measuring-system.

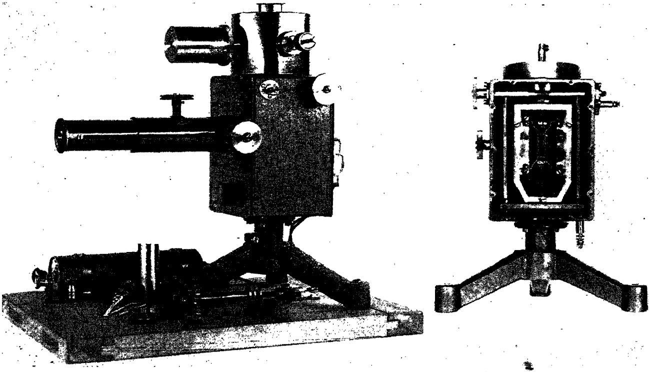


FIG. 2.—General and interior views of Wulf type of bifilar electrometer.

For permanent and continuous recording of potential-gradient, apparatus must be installed in a suitable shelter, preferably a substantial observatory-building, and allowance made for the distorting effect of the building on the Earth's field. The radioactive collector is mounted at the end of a rod which projects from a hole in a wall (or the roof) of the building, the rod itself being supported in the wall in appropriate insulators (amber or sulphur). Within the building the rod is connected to the measuring-system of an electrometer. The electrometer for this permanent installation may very well be a Dolezalek quadrant-electrometer [572], as arrangements for photographically recording the thing being measured are easily made. The measuring-system of the Dolezalek

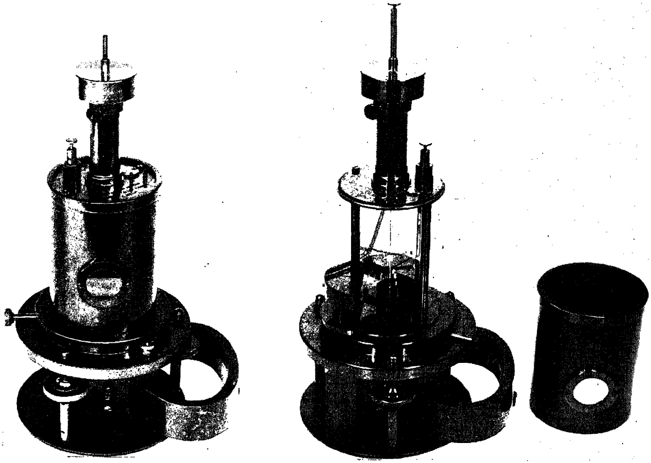


FIG. 3.—General and interior views of Dolezalek quadrant-electrometer.

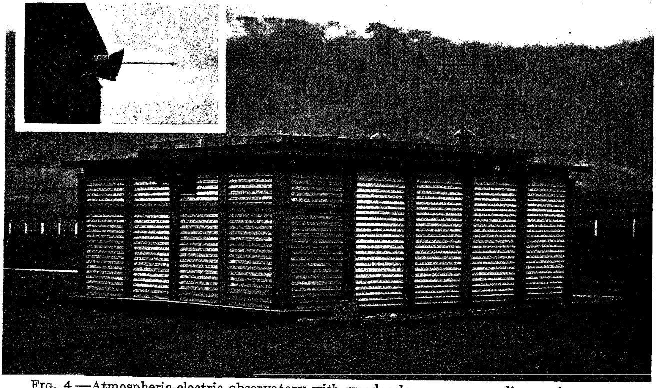


FIG. 4.—Atmospheric-electric observatory with wooden louvers surrounding an inner concrete structure with 50 cm air-space between; insert shows potential-gradient collector-rod with ionium collector-disk at tip and tubular hood to protect insulators and automatic relay.

electrometer consists of a "needle" suspended from an insulated hook by a fine phosphor-bronze strip. For reliable potential-gradient measurement the insulator holding the hook must be of amber. With the electrometer properly set up the needle hangs symmetrically within a shallow cylindrical chamber cut into quadrants. The quadrants are insulated from base and case of the electrometer. Alternate quadrants are electrically connected and, with a constant potential-difference from a battery, having its mid-point connected to the case and to earth, across the two pairs of quadrants, any potential applied to the needle will cause the needle to turn an amount proportional to the applied potential. The mirror attached to the needle-suspension then reflects a spot of light onto

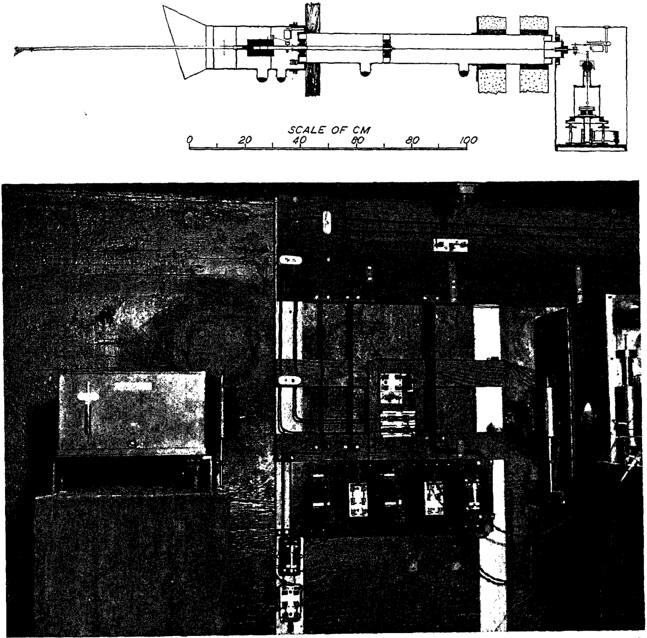


Fig. 5.—Recording potential-gradient apparatus and schematic diagram of collecting-system and electrometer.

a visual scale or onto a sheet of photographic paper and reveals the changes which occur in the potential of the needle. Figure 3 shows views of the Dolezalek quadrant-electrometer. Figure 4 shows the exterior of an observatory-building with potential-gradient collector mounted on a wall, as used at observatories of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington [570]. Figure 5 gives additional details of the same apparatus, showing the metal box in which the electrometer is housed to protect it from dust and dirt, another metal box which houses a cylinder that rotates once in 24 hours to give a daily sheet of potential-gradient record, a lamp (near the recorder-box) which produces the recording light-spot, and various controlling relays and switches. Figure 5 is a schematic diagram of the collector-system and electrometer. The collector-system is in this case a long affair since the building, to minimize temperature-variations, consists of a concrete structure set within a wooden ventilating structure with 50 cm of air-space between the two. Amber insulators are used throughout the collector-system and are indicated as dark areas in Figure 5.

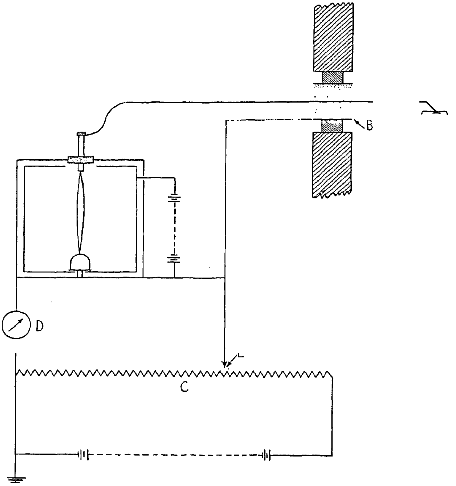


FIG. 6.—Schematic diagram of potential-gradient apparatus using the null-method of measurement.

Today no automatic recording-device is completely effective without the various automatic controls which can be easily arranged. So-called "program-machines," electrically operated and actuated by an accurate pendulum clock, which will ring bells, light lights, and open and close circuits at any minute of the day or night, are readily procurable.

The relays seen on the wall of the room in Figure 5 are actuated by a program-machine. One functions every hour at the hour to earth the electrometer-needle for a period of a minute to provide a base-line from which to measure electrometer-deflections; another functions to provide a ten-minute insulation-test every four hours; and the third closes to light a light exactly on the hour to provide time-control marks on every photographic record. With each relay is associated a switch which permits the investigator to do manually, at any desired time, what the program-machine does automatically. There is an additional relay for the potential-gradient apparatus (lowest in Fig. 5) which may be put into service as required and which permits the recording-lamp to burn momentarily at regular intervals (once every minute or two) and thus makes the photographic record appear as a line of dots rather than as a continuous line. This is very useful when eye-readings at some field-station are to be compared with the permanent recording-apparatus, as is the case when standardizing observations (to get the effect of distortion caused by the observatory-building) are made. It may be mentioned here that with the collector-system mounted as shown in Figures 4 and 5—collector-disk 2.45 meters above ground-level and 1.00 meter out from the wall of a flat-roofed building three meters high, with the wall carefully covered by earthed wire screen—the recorder gives values only ten per cent lower than values obtained with field-apparatus on an open, level site in the vicinity. The distorting effect of the building is thus made small by the arrangement of the equipment.

Null or compensating methods of measurement have certain advantages over direct measurements in some types of work, and in potential-gradient observations taken with an eye-reading instrument the advantage is considerable. The null method [561] makes it unnecessary to maintain the high degree of insulation that other methods require. True, quite good insulation is still required, but the instrumental arrangement shown in Figure 6 eliminates tendency for leak across insulators of amber or sulphur by keeping all metal parts in which the insulators are mounted at about the same potential as that acquired by the insulated collecting- and measuring-system. This balancing of potentials is accomplished with the aid of auxiliary equipment including batteries, a moderately high resistance, *C*, with a sliding-contact, *E*, a voltmeter, *D*, and a guard-ring, *B*, the latter surrounding the insulator in which the collector-rod is mounted. In the case of the stretched-wire apparatus, the shells of the insulators supporting the stretched wire become the guard-rings. In the null method, the electrometer-deflections are always restored to a "zero-position"—the position of the electrometer-fibers when the collector-system is earthed—by moving the contact, *E*, and the potential is then read from the voltmeter. Besides reducing difficulties of insulation, the method also eliminates need for electrometer-calibration and, since potentials are obtained directly in volts, the work of converting electrometer-readings to volts is eliminated.

The instruments and apparatus thus far described have been devised primarily for investigations of the potential-gradient during fair weather. When bad weather prevails and there are heavily charged clouds over the sky, or thunder-storms are in progress near-by or in distant regions, the potential-gradient varies tremendously in magnitude and changes sign with extreme rapidity. Apparatus for potential-gradient measurements under these conditions was devised by C. T. R. Wilson in 1914 [786], one instrument being known as the "elevated-sphere" apparatus and the second as the "test-plate" apparatus. Wormell in 1927 [790] devised apparatus utilizing an elevated sharp point rather than an elevated sphere and this, with the test-plate apparatus, has been adopted for continuous use at Kew Observatory of the British Meteorological Office [621]. Schonland, who discusses the electricity of thunder-storms and shower-clouds in Chapter XII, and his colleagues have used the elevated-sphere, test-plate, and point-discharge instruments [763, 764, 771] for the studies from which have come their outstanding and interesting contributions to our knowledge of atmospheric electricity.

The elevated sphere, as it has been much used, is a hollow copper ball 30 cm in diameter mounted at the top of, but well insulated from, a supporting rod five meters high. The rod is hinged at the bottom so that the sphere may be lowered into an earthed metal box or enclosure. The elevated-point apparatus is similarly arranged, but an insulated pointed wire replaces the sphere. The test-plate is a circular container 50 cm in diameter filled with earth in which is embedded a metal plate. The container is set in a circular hole in the ground but well insulated from the ground, with its upper surface level with the ground. From each of these collectors—sphere, point, and test-plate—a wire runs through the hollow supporting-tube and through conduits to insensitive electrometers located in an observing-hut some meters distant. The wire is supported at intervals along its course in insulators of quartz. Figure 7 is C. T. R. Wilson's drawing of a sphere and test-plate installation, and Figure 8 is a very simple schematic diagram of the test-plate apparatus. In Figure 8, *M* represents the capillary electrometer which Wilson devised for his apparatus, *A* is the test-plate, and *C* the earthed metal cover which, as seen from Figure 7, may be swung over the test-plate as desired, to shield it from the Earth's field. With these pieces of apparatus it is possible to study the variations in the Earth's field due to lightning-flashes and to the charges on storm- and shower-clouds and to understand something of the interchange of electricity between the Earth and air that takes place in threatening or bad weather.

Of the different types of potential-gradient apparatus, it may be said in a general way that the radioactive type of collector is most suitable for measurement of the small, relatively steady potential-gradients found in fair weather; the sphere or point-discharger is most suitable for studying the larger and more variable gradients associated with mild or distant thunder-storms; and the test-plate is really required for observations of the largest and most variable gradients encountered with violent or near-by thunder-storms.

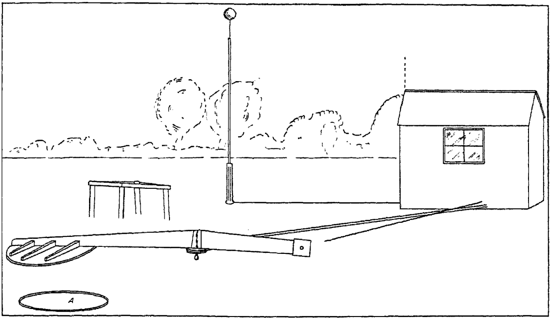


Fig. 7.—C. T. R. Wilson's elevated sphere and test-plate apparatus for potential-gradient measurements.

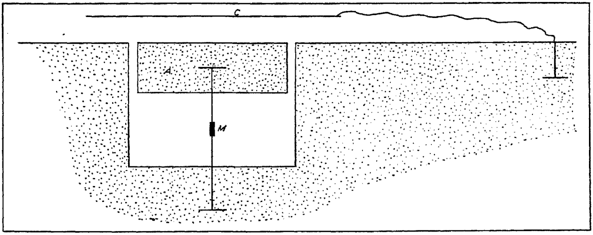


Fig. 8.—Sketch of C. T. R. Wilson's potential-gradient test-plate apparatus.

III. CONDUCTIVITY-APPARATUS

The electrical conductivity of the atmosphere near the Earth's surface, which is due almost wholly to the molecular or small ions in the air, has been dealt with at some length by Hess [633] in his book on the subject, in which he discusses and describes the various types of apparatus for its measurement. The earliest direct measurements of electrical conductivity of the air date only from the beginning of the present century, following upon the development of the ionic theory of gases. Various instruments for measurements of conductivity have been devised, one of the simplest and most used being that of Gerdien [559] which is shown diagrammatically in Figure 9.

The apparatus consists essentially of two concentric cylinders, the outer one being about 60 cm long and 16 cm in diameter and the inner one about 25 cm long and 1.4 cm in diameter. The outer cylinder is connected to Earth and the inner one is insulated (with amber) and connected to an electrometer of low capacity and suitable sensitivity. When the inner cylinder, which is capped at both ends, is charged with electricity of either sign to, say, 50 volts with respect to the outer cylinder and to Earth, and air is drawn through the large cylinder by a fan operated by hand or clockwork or electric motor, the inner cylinder acts as a "collector" for it attracts ions of sign opposite to that of the charge on it. From the rate of decrease, thus caused, of potential-difference between the two cylinders, as derived from simultaneous observations of potential-difference and time, the unipolar conductivity (positive or negative, as the case may be) is readily computed, suitable allowance being made for the natural leak of the apparatus. The important restriction must be made in conductivity-measurements of this kind that, for a given rate of air-flow through the apparatus, the potential initially applied to the inner cylinder must be less than is required to produce "saturation-current" between the inner and outer cylinders. If a saturation-current is produced, the instrument ceases to be a conductivity-apparatus and becomes an ion-counter, counting the number of molecular ions of a given sign in the

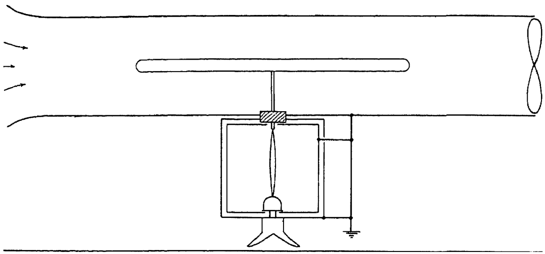


FIG. 9.—Sketch of Gerdien conductivity-apparatus.

volume of air passed through the apparatus. In field-observations of conductivity, as in those of potential-gradient, it is convenient to use a bifilar electrometer of the Wulf type as the measuring instrument. A Wulf unifilar electrometer or one of the Lutz type is also suitable, and more will be said of these later.

For a permanent installation, when it is desired to measure the electrical conductivity of the air continuously over a period of months or years, equipment such as that shown in Figure 10 serves very satisfactorily. In this Figure the apparatus is set up for testing; the rough wooden structure simulates one end of an observatory-building through the roof of which the cone-capped air-flow tubes will protrude in the final installation. The apparatus consists of two separate but similar units which, operating simultaneously and continuously, record both the negative and positive conductivities. Each unit is a Gerdien apparatus installed with its axis vertical, with inner and outer cylinders of the dimensions already given except that the outer cylinder is not now 60 cm long but is extended up through the roof and down through the floor so that air may be drawn in from above the observatory-building and exhausted below the raised floor. The apparatus is used in a darkened room, photo-

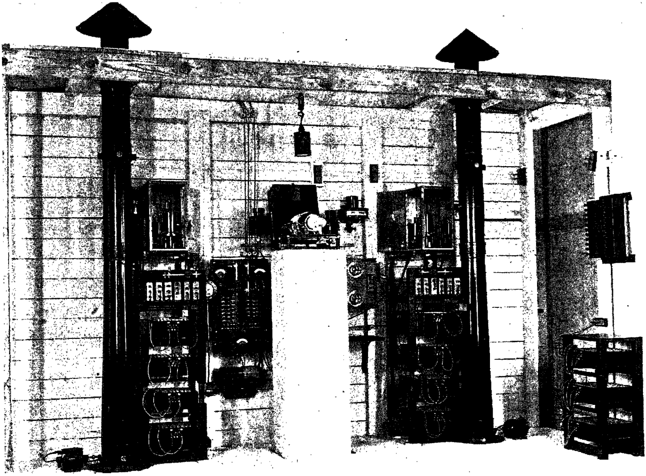


FIG. 10.—Recording conductivity-apparatus with calibrating potentiometer.

graphic paper being exposed, upon which are recorded the movements or deflections of the two spots of light proceeding from the quadrant-electrometers which are used as the measuring instruments. Both spots record upon the same photographic sheet, the sheet being mounted on a rotating drum installed on a concrete pier midway between the two units of the apparatus. A clock mechanism rotates the drum once in 24 hours (the rotation may be changed by a simple gear-shift to once in three hours), so that each sheet represents one complete day's record of both positive and negative conductivities.

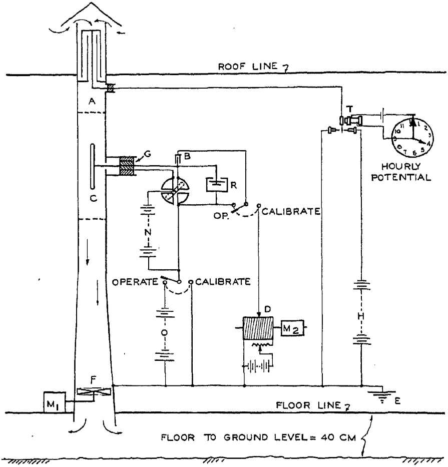


FIG. 11.—Schematic diagram of recording conductivity-apparatus with calibrating potentiometer.

A schematic diagram of a single unit is shown in Figure 11. The air is drawn through the outer cylinder, hereafter designated as the air-flow tube, by a motor-driven fan, *F*, placed in the tube at the floor-level of the building. The inner or central cylinder, *C*, which is insulated from the air-flow tube by an insulator of amber, is connected to one pair of quadrants of the electrometer, the other pair of quadrants being connected to the case of the electrometer, which is insulated and maintained at a constant potential of 100 volts or less by battery *O*. Across the two pairs of quadrants is permanently connected a high-resistance radioactive cell, *R* (10^{12} ohms), of the type modified by W. F. G. Swann and S. J. Mauchly [680]. With proper potential applied to the electrometer-needle from battery *N* (seldom more than 100 volts) and with the arrangements as outlined, when air is drawn with sufficient velocity through the air-flow tube the electrometer experiences a continued deflection, the magnitude of which is determined by the conductivity of the air, the potential applied to the central cylinder, *C*, the resistance of the radioactive cell, and the sensitivity of the electrometer. The apparatus measures either positive or negative conductivity, according to the sign of the potential applied to the central cylinder. To a guard-ring, *G*, is applied the same potential as is applied to the central cylinder, and leak across the amber supporting the central cylinder is thus minimized.

In order to determine the base-line from which the electrometer-deflection produced by the conductivity shall be measured or, in other words, to determine the deflection corresponding to zero-conductivity, a set of concentric cylinders is mounted in the upper portion of the air-flow tube. This set of cylinders is arranged and connected up in such a way as to form a cylindrical condenser, *A*, of electrical capacity much greater than that of the condenser-unit formed by the central cylinder and air-flow tube. Condenser *A* is conveniently termed the auxiliary condenser. Once every hour a potential of about 300 volts is applied across it, for a period of three to five minutes, from a battery, *H*, through the operation of the relay *T*. At those times, all the ions of mobility greater than 0.1 cm per sec per volt per cm are drawn out of the air, so that no ions get to the central cylinder, and the electrometer-deflection falls to a position representing zero-conductivity of the air.

This zero will not coincide with that obtained by removing the potential from the central cylinder, *C* (as is done to get the calibrating-zero), for with a potential on it the central cylinder will still collect ions which are being generated by radioactive material deposited on the surfaces of the air-flow tube and central cylinder, so that a residual conductivity arises which separates the true conductivity-zero from the calibrating-zero. That there should be a difference between the two zeros is not important, but it is interesting to know how such a difference is brought about.

According to the theory of Gerdien, the ions which are drawn to the central cylinder when the apparatus is operating come from a region which is bounded by a cylindrical surface. The cross-sectional area of this region is inversely proportional to the velocity, *U*, of the air and is directly proportional to the potential-difference, *V*, between the outer and central cylinders, to the *measured* capacity, *C*, of that part of the central-cylinder system which is exposed to the air-current, and to the specific velocity, *v*, of the ions in question. So long as the calculated radius of this cross-sectional area is less than the radius of the outer cylinder of the apparatus, the apparatus measures the true conductivity.

To calculate the radius, we have the formula

$$r^2 = 4CVv/U \tag{1}$$

and, for the apparatus here being described, C is about six cm, V is usually less than 100 volts, and U is not less than 200 cm per sec. As v is known to be close to 1.5 cm per sec per volt per cm at sea-level, r is found to be less than five cm whereas the radius of the air-flow tube is eight cm.

Swann has shown [679] that C must be the *measured* value of the capacity of that part of the central-cylinder system, including the supporting rod, which is exposed to the air-current and cannot be computed from the dimensions of the apparatus. This applies not only in the case of the calculations made above, but also for the computations of the true conductivity from the formula developed by Riecke [575].

According to Riecke, a charged sphere placed in a stream of air of sufficiently high velocity so that effects of diffusion, re-formation, and recombination of ions may be neglected loses its charge at a rate given by

$$-dQ/dt = 4\pi Q\lambda \tag{2}$$

where Q is the charge on the sphere and λ is the unipolar conductivity. Swann [679] showed that this formula applies not only to a charged sphere but also to a charged body of the shape of the central cylinder of a Gerdien conductivity-apparatus.

For the conductivity-apparatus $Q = VC$, where V, as previously defined, is the potential-difference between the central cylinder and the air-flow tube and C is the *measured* capacity of that portion of the central-cylinder system and its support which is exposed to the air-current. Formula (2) then becomes

$$-dQ/dt = 4\pi CV\lambda \tag{3}$$

Now, the quantity dQ/dt is the rate of passage of electricity through the high-resistance radioactive cell and is readily obtained by means of calibration-equipment attached to the conductivity-apparatus.

Referring again to the schematic diagram in Figure 11, there is connected to that part of the circuit which includes the central cylinder, the insulated pair of electrometer-quadrants, and the upper electrode of the radioactive cell, the inner member of a small cylindrical condenser, B. The outer member of this condenser is connected to a rolling contact which runs on a wire spirally wound on a drum, D, the drum being rotated when in use [569]. One end of the spiral-wound wire is connected to Earth and to one side of a battery, the other end being connected to the other terminal of the battery.

During calibration the air-flow is shut off and the battery, O, supplying potential to the central cylinder is disconnected.

With a potential-difference maintained across the ends of the spiral wire and the latter revolved so that the rolling contact moves along it, the electrometer will deflect and eventually, if the rotation of the drum is uniform, a steady deflection will be attained which is determined by the resistance of the radioactive cell, the rate of alteration in potential of the moving contact, and a quantity, k, representing the capacity of the condenser, B. If dV/dt is the rate of alteration in potential of the moving contact, we have, with the value of k, a kdV/dt represented by a particular steady deflection. For an equal deflection during measurement of electric conductivity of the air, represented by dQ/dt, we may write

$$-kdV/dt = dQ/dt = 4\pi CV\lambda \tag{4}$$

From this equation a value of conductivity corresponding to a particular electrometer-deflection is readily obtained. As constructed and operated, the calibration-apparatus gives the following values for equation (4). The capacity, k, of the calibrating-condenser is about 16 cm; there are 70 turns of wire on the calibration-drum; the speed of rotation of the drum is about 12 r.p.m. or one-fifth of a revolution per sec, and is kept as precisely as possible at the same value on all occasions by adjusting the speed of the driving motor to give a constant tachometer-reading. The voltage across the wire on the calibration-drum may have any value up to 30 volts; usually it is applied in steps of three or four volts so that six or seven calibration-points are obtained in each calibration-period. If, for example, the voltage across the drum is taken as ten volts, kdV/dt becomes (not converting volts to ESU) 0.46. For conductivity then, we have $\lambda = 0.46/4\pi CV$, where V must be in volts. As C has earlier been given as six cm and V, the voltage across the central cylinder and air-flow tube during regular conductivity-measurements, may be taken as, say 20 volts, λ becomes 0.46/1,508 or 3.05×10^{-4} ESU. For this value of conductivity we can now find what the electrometer-deflection will be for a given sensitivity of the electrometer and given resistance of the radioactive cell. Converting the value 0.46 to ESU by dividing by 300 we obtain 15.3×10^{-4} ESU of current. If the cell-resistance is 10^{12} ohms, or 1.1 ESU of resistance, the voltage-drop across the cell will be 16.8×10^{-4} units of potential which is equal to one-half volt. If the sensitivity of the electrometer, as measured on the photographic sheet at a distance of one meter from the electrometer, is 60 mm of deflection per volt, the deflection will be 30 mm. Other voltages across the drum give other values of conductivity with other deflections from which a suitable calibration-curve may be drawn.

From the foregoing it will be seen that the major items of equipment in the apparatus are: (*a*) The air-flow tube, containing the auxiliary condenser and the air-flow fan; (*b*) the central cylinder; (*c*) the electrometer;

(*d*) the radioactive cell; (*e*) the calibration-apparatus, including calibrating-condenser and revolving drum; and (*f*) batteries required to supply potentials to various parts of the apparatus.

Automatic devices to make time-marks on the photographic sheet and to apply potential to the auxiliary condenser once each hour so that a zero-conductivity deflection may be recorded are important accessories to be operated, where possible, by a program-machine such as was mentioned in connection with the potential-gradient recorder.

The high-resistance cell used with the conductivity-apparatus is a modified form of the cell developed by Bronson [555]. A cylindrical chamber about 20 cm in diameter and 20 cm high is silver-coated inside. On the base of the cell is a circular area coated with thorium ionium nitrate salt, containing eight to ten per cent ionium, applied in the same manner as is used for preparing radioactive collectors for potential-gradient work. The ionium-surface is sealed over by a very thin disk of mica and the mica is covered by a disk of silver foil. Through the top of the cell project two concentric rods (set in an insulator of amber) terminating in small disks mounted with faces parallel to the base of the cell. These two electrodes, silver-coated like the chamber, may be adjusted independently of each other with respect to the cell-base. Alpha particles from the ionium make the air within the cell slightly conducting and the positions of the electrodes may be varied to alter the resistance of the cell over a considerable range. The positions of the two upper electrodes may also be adjusted to obtain approximate linearity between calibration-deflections on the photographic sheet and the several voltages applied across the uniformly rotated calibrating-drum to produce the different deflections. The adjustment of the radioactive cell is affected by variations in temperature and pressure. The pressure-effect can usually be neglected, but the temperature-effect is such that the cell should be used in a temperature-controlled location whenever possible; otherwise tedious temperature-corrections to observational data may be required.

A more compact form of conductivity-apparatus [549] can be devised than that shown in Figure 10, as is evidenced by the view of the apparatus in Figure 12. In this Figure the air-flow tube is not shown, nor is the cabinet which houses batteries and upon which the instrument stands. At the left is the metal box in which are mounted the high-resistance radioactive cell and a unifilar electrometer of the Lutz type. In the Lutz electrometer a single quartz fiber, coated with conducting material, is mounted midway between two metal plates across which a potential may be applied. The fiber is supported at the top by a post set in an insulator of amber and at the bottom is attached to a non-conducting quartz ring. The sensitivity of the electrometer may be adjusted within fairly wide limits by changing either the tension on the fiber, the distance between the plates, or the potential across the plates. The deflection of the fiber is noted against a scale in the eyepiece of the observing telescope or, when it is desired that a photographic record be obtained, a light is placed at a window in the back of the electrometer-case and the shadow of the fiber is thrown upon the photographic sheet through the lens-system of the telescope to make a white line against the black exposed sheet. The Wulf unifilar electrometer could also be used in this apparatus as it differs in no essential way from the Lutz, the chief difference being that the fiber is held at its lower end by a quartz bow instead of a ring.

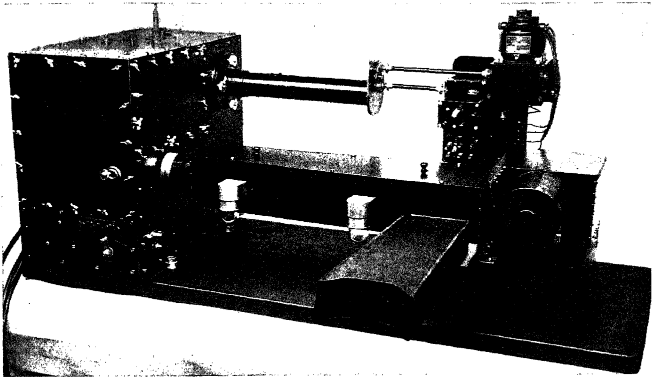


FIG. 12.—Recording conductivity-apparatus with calibrating condenser.

Referring to Figure 12, the recording light shines through the electrometer and through the light-proof rectangular tube to the photographic sheet in the cylindrical container at the right. At the back of the cylinder is the clock which rotates the drum carrying the photographic sheet inside the cylinder. A viewing hood attached to the light-tube permits the observer to view the position of the electrometer-fiber at any time. This apparatus may be operated in bright light, unlike the apparatus in Figure 10.

Above the light-tube is seen the calibration-apparatus. It consists of a variable cylindrical condenser, one element being made to move by a motor at a steady rate, to give a uniform change in capacity with time. In this case, then, the variable condenser takes the place of the rotating slide-wire potentiometer used with the apparatus previously described, and a constant potential is applied between the moving cylinder of the condenser and Earth. For calibration we have, then, Vdk/dt instead of the *kdV/dt* of the former case. For different values of potential between the condenser and Earth, different calibration-points are obtained. The wiring of the apparatus is shown in Figure 13, where it is seen that the circuits are very little different from those in Figure 11, even though the quadrant-electrometer has been replaced by a unifilar instrument, *K*, and the rotating slide-wire by a variable condenser, *N*. In this diagram, *D* is the roof of the building and *B* indicates screens in the air-flow tube for protecting the central cylinder from insects, lint, and dirt. *Z* is the amber-insulator supporting the fixed element of the calibrating-condenser and *R* is the guard-ring for that insulator. *Q* is the moving element of the calibrating-condenser. Other letters designate parts familiar from previous description.

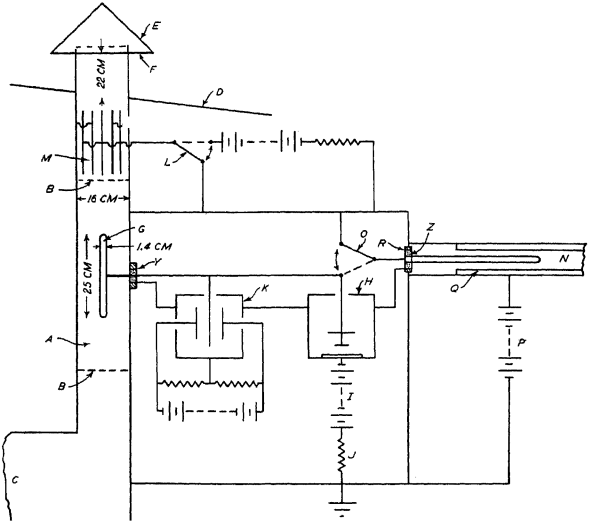


FIG. 13.—Schematic diagram of recording conductivity-apparatus with calibrating condenser.

Another adaptation of the Gerdien conductivity-apparatus is that used on the stratosphere flight of the balloon *Explorer II* on November 11, 1935 [631]. As shown in Figures 14 and 15, *A* is the air-flow tube, supported by the tube *E* on the outside surface of the gondola of the balloon. A fine wire through *E* connects the amber-insulated central

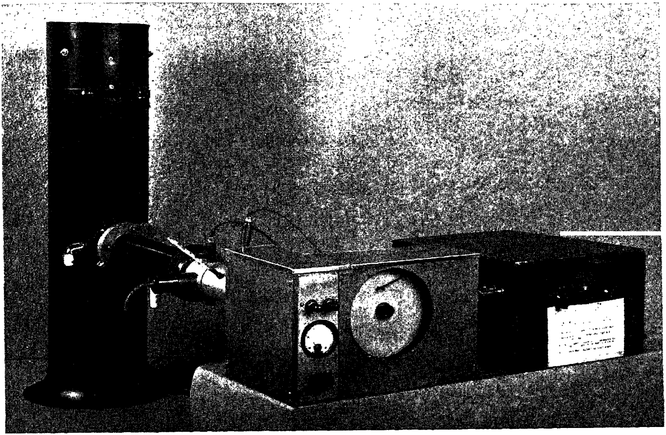


FIG. 14.—Recording conductivity-apparatus for stratosphere measurements.

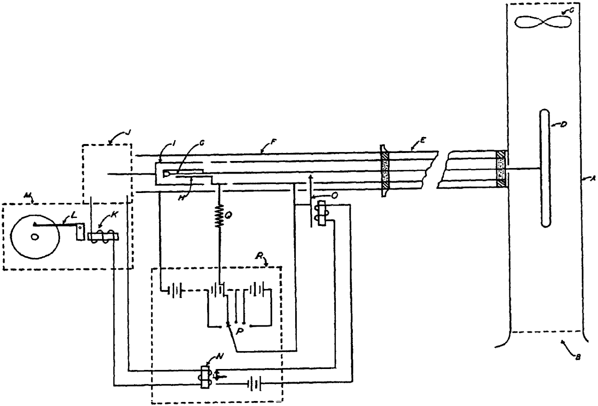


FIG. 15.—Schematic diagram of conductivity-apparatus for stratosphere measurements.

cylinder, *D*, with the electrostatic pilot, *F*. The pilot, the amplifier, *J*, the recorder, *M*, the charging-device, *O*, and the battery-box, *R*, were located inside the gondola. The electrostatic pilot consists essentially of three parts, *G*, *H*, and *I*. *G* is a coated quartz fiber of the type used in the Wulf unifilar electrometer, *H* is a charging-plate parallel to the fiber and very near it, and *I* is a cylinder which with *G* or *H* forms a condenser that connects with the amplifier, *J*. After the central cylinder, *D*, is initially charged, ions representative of the conductivity of the air collect on it and eventually neutralize its charge. The fiber, *G*, deflects gradually and finally touches *H* and, being charged again, immediately deflects away. In the moment of contact of *G* with *H* the amplifier, a two-stage resistance-coupled type, amplifies the charging-pulse and the electromagnets, *K* and *N*, are then actuated. *N* in turn actuates the electromagnet at *O*, and *O* recharges the collector-system more surely and accurately than does the momentary contact of *G* with *H*. The electromagnet, *K*, displaces the pen, *L*, from its normal position at each pulse, so that the frequency of the displacement-marks on the paper disk of the recorder is proportional to the electrical conductivity of the air. Accurate time-control is obtained on the record by displacing the pen in the direction opposite to that for recording, by means of the master time-control system in the gondola.

IV. ION-COUNTERS

At the outset it must be pointed out that ion-counters do not count ions; they count number of unit-charges of electricity (4.77×10^{-10} ESU), positive or negative as the case may be, accumulated on the collector-system of an apparatus over a definite period of time. When accurate determination is made of the volume of air passed through the counter during the specified period, it is possible to compute the number of unit-charges contained in unit-volume of the air-sample. It is then assumed that only one unit-charge is carried by each electrified particle, or ion, so that the number of ions is taken as equal to the number of charges.

An ion-counter, then, requires a collecting-system, a measuring-system, a fan driven by hand, clockwork, or electric motor, for drawing air through the collector-system, and a meter for accurately determining the volume of air passed through the counter during an observation.

It will be recalled that, earlier in this Chapter, the statement was made that the conductivity-apparatus might function as an ion-counter if, for a given potential between the air-flow tube and central cylinder, the air-flow was permitted to be so slow that all the ions in the air passed through were drawn out. However, the dimensions of the air-flow tube and central cylinder of the conductivity-apparatus are not convenient for ion-counting, and ion-counters generally have an air-flow tube of much smaller diameter and a central cylinder correspondingly reduced in diameter.

The dimensions of the air-flow tube and central cylinder, the potentials applied across them, and the rate of air-flow chosen for an ion-counting apparatus are governed by the kind of ions to be collected. Three classes of ions are recognized as residing in the atmosphere near the Earth's surface, which are known as small, intermediate, and large ions. All three are discussed in detail in Chapter IV, and little need be said here about them except as regards their rate of travel in an electric field. Small ions have a velocity at sea-level of about 1.5 cm per second in a field of a volt per cm; intermediate ions have varying velocities depending apparently on the vapor-pressure [668, 690] but with an average velocity less than 0.1 cm per sec in the same field; and large ions have a velocity of approximately 0.0003 cm per sec per volt per cm. Small ions, then, travel perhaps 10 to 20 times as fast as intermediate ions, and several thousand times as fast as large ions, in the same electric field.

With ion-velocities covering so great a range, it is not practical to have one instrument for studying all three classes of ions. The so-called small-ion counter which has been much used can be made to count both small and intermediate ions, but a separate instrument is necessary for counting the large ions. A view of the small-ion counter is given in Figure 16. The essential features seen are the air-flow tube, the Lutz type of unifilar electrometer, the air-flow meter (anemometer) connected at the base of the air-flow tube, and the cylinder at the right of the electrometer in which is contained a spring-driven air-flow fan. The hemispherical cap on the air-flow tube has a screen on its under side through which the air enters the counter. Now, there is an advantage in constructing the air-flow system of an ion-counter somewhat differently from the air-flow system of a conductivity-apparatus. In the conductivity-apparatus the central "collecting-cylinder" is given a charge of some 20 to 100 volts, whereas in the ion-counters to be discussed here the central cylinder is always earthed at the beginning of an observation and never has more potential on it than is derived from the charges collected. While this potential may become as great as 10 or 15 volts with respect to Earth in, say, an hour of continuous measurement, such voltages are low enough to minimize insulation break-down in the apparatus. To use the ion-counter with its central cylinder earthed, it is desirable to surround the air-flow tube with an earthed jacket and to apply between the air-flow tube and outer jacket the potential which would otherwise have been applied across the central cylinder and air-flow tube. In Figure 16, therefore, the tube seen is not the air-flow tube but the outer earthed jacket, within which are the air-flow tube and the central cylinder or rod. This arrangement may be understood better upon inspection of Figure 17, where the small-ion counter is shown at the extreme left, together with the unifilar electrometer and an anemometer. The other piece of apparatus shown is a large-ion counter which will presently be described.

With details as given in Figure 17 for the small-ion counter-tubes, the effective electrical capacity of that part of its air-flow system exposed to the air-flow has been found indirectly to be about five cm and, with an air-flow of, say 1,000 cc per sec (velocity 145 cm per sec), it can be determined from equation (1) that a potential of 16 volts across the outer jacket and the air-flow tube will drive to the central rod all small ions, of the same sign as the potential on the air-flow tube, having a specific velocity (mobility) greater than 1.0 cm per sec per volt per cm.

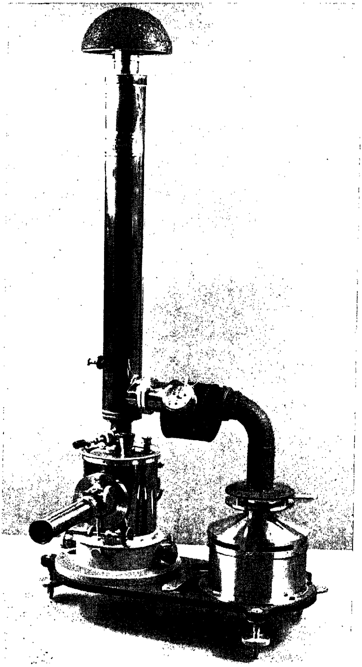
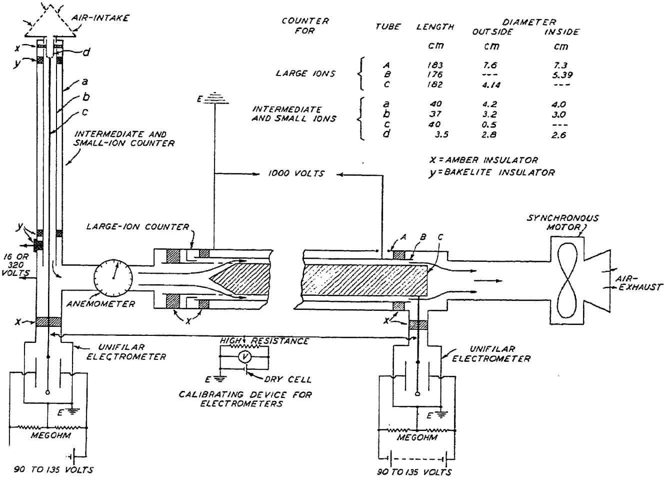


Fig. 16.—Small- and intermediate-ion counter with Lutz type of unifilar electrometer.

If, now, intermediate ions are to be collected by the same apparatus, 320 volts applied across the earthed jacket and the air-flow tube will cause all ions of one sign having mobility of 0.05 cm per sec per volt per cm or greater to be collected by the central rod, and this will usually include all intermediate ions of a given sign found in the free atmosphere as well as all the small ions of the same sign.

It is possible, then, during one observing-period (say an hour) to measure small-ion content with about 16 volts across the cylinders and, in the next similar period, to measure the sum of small and intermediate ions with 320 volts across the cylinders.



COUNTER FOR	TUBE	LENGTH	DIAMETER OUTSIDE	DIAMETER INSIDE
		cm	cm	cm
LARGE IONS	A	183	7.6	7.3
	B	176	---	5.39
	C	182	4.14	---
INTERMEDIATE AND SMALL IONS	a	40	4.2	4.0
	b	37	3.2	3.0
	c	40	0.5	---
	d	3.5	2.8	2.6

X = AMBER INSULATOR
y = BAKELITE INSULATOR

FIG. 17.—Schematic diagram of ion-counter for small, intermediate, and large ions.

From such a procedure the number of intermediate ions of a given sign in each cc of the air may be deduced, but a more satisfactory method involves the use of an auxiliary cylindrical condenser. It will be recalled that in the conductivity-apparatus an auxiliary condenser, *A*, Figure 11, attracts all small ions once each hour to provide a deflection representing zero-conductivity. In a similar way, if the air-intake cap shown in Figure 17 is removed and an auxiliary condenser is mounted on top of the small-ion counter, the small ions may be drawn out of the air being sampled so that the small-ion counter will count only intermediate ions. If the auxiliary condenser is in this case another set of tubes just like the set on the small-ion counter itself and the central rod is electrically connected to the earthed outer tube, 16 volts applied across this condenser will sweep out all the small ions and leave only the intermediate ions to be counted. If the auxiliary condenser is operated alternately with and without a potential across its cylinders for definite periods, values of small-ion content are readily derived from the difference between the measurements in the two cases.

In the counter for small and intermediate ions the central rod is initially earthed and a charge then builds up on the rod and electrometer through the period of observation, as has been mentioned. If the apparatus is continuously operated and photographic records obtained of the moving fiber and if a "program" machine is available to earth the central rod at regular intervals and to apply a potential to the auxiliary condenser for alternate periods of recording, very satisfactory ion-counts may be obtained.

For computing the number of small or intermediate ions present per cc of air, we have the formula

$$n = (CdV/dt)/300eW \tag{5}$$

C here is the measured capacity of the air-flow system and the electrometer, which is 30 cm, e is the electronic charge, and W, as before, the air-flow of 1,000 cc per sec. dV/dt depends on the period of observation, the sensitivity of the electrometer, and the recorded deflection. When a record is obtained for one hour (3,600 sec), and the electrometer-deflection is, say, 36 mm and the electrometer-sensitivity three mm per volt, $dV/dt = 0.0033$ volt. This value being used in equation (5), n becomes 692 ions which, if no potential was applied across the auxiliary condenser, represents 692 small and intermediate ions per cc.

The electrical capacity, C, in the above computation, representing the capacity of the air-flow system and the electrometer, must be a measured and not a computed quantity. Its value, while depending chiefly on the dimensions of the cylinders, is considerably affected by the design of the cup, d, of Figure 17, at the top of the central rod, and by the manner of attaching the cup to the rod. The effect of different cups may be as much as 10 or 20 per cent.

Turbulence in the air-flow tube is a factor in the effective capacity (about five cm in this case) of that portion of the apparatus exposed to air-flow, the result of increased turbulence being to reduce the effective capacity or, in other words, to require greater potential across the cylinders of the air-flow system to draw out all the ions. As the required potential cannot be safely computed under such circumstances, it must be indirectly found by placing a series of potentials across the air-flow system and determining at what value of potential the apparatus shows no further increase in deflection with increase in potential. By applying a potential during ion-measurements somewhat in excess of the value so determined, the apparatus may be expected to function correctly.

In Figure 17 a large-ion counter is shown coupled with the small-ion apparatus so that the same sample of air is examined with both instruments. Figure 18 is a view of the coupled counters [584]. Since the large ions are slow-moving, the cylinders of the air-flow system must be comparatively long, the space between the central cylinder and air-flow tube quite small (6.2 mm from the dimensions given in the Figure), and the potential applied across the outer jacket and the air-flow tube relatively high. When the air-flow is 1,000 cc per sec and the effective electrical capacity of that part of the apparatus exposed to the air-flow is 345 cm as in this case, it can be shown [with equation (1)] that the potential necessary to extract all large ions with mobility of 0.0003 cm per sec per volt per cm, or greater, from the air passed through the counter is 750 volts.

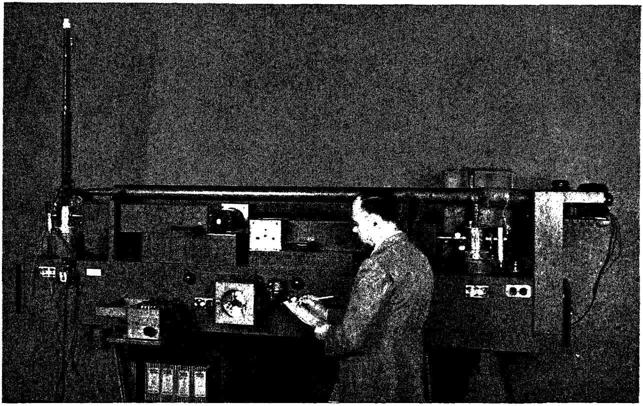


FIG. 18.—Ion-counter for small, intermediate, and large ions.

The charges collected by the central cylinder of the large-ion counter are not permitted to accumulate, as in the small- and intermediate-ion counter, but leak off to ground through a high-resistance radioactive cell identical with that used with the conductivity-apparatus. The upper electrode of the cell is connected to the central cylinder and electrometer-fiber, while the lower electrode is connected to Earth. When large ions are being counted, the electrometer-fiber is deflected, owing to the flow of the ionic charges to Earth, to a position depending on the potential-drop across the cell.

The large-ion counter is calibrated with a variable cylindrical condenser like that shown with the conductivity-apparatus in Figure 12. Calibrations show that with air-flow of 1,000 cc per sec, cell-resistance of 10^{12} ohms, and electrometer-sensitivity of 30-mm deflection per volt on the photographic sheet placed one meter distant from the electrometer-fiber, a deflection of one mm during regular recording represents 1,200 large ions of one sign per cc of air. Once each hour the air-flow fan is stopped by automatic control and, as no ions are then being collected, the electrometer-deflection falls to a position representing zero ion-content. These hourly zero-deflections provide the base-line from which the deflections representing large-ion content of the air are measured.

Ion-counters and conductivity-apparatus may be found of various sizes and designs, but in all of them samples of air are passed between charged plates or cylinders and the electrified particles drawn out and collected on some form of electrometer or electroscope. Adequate insulation, correct determinations of electrical capacities of apparatus, accurate determinations of applied potentials and of the volumes of air sampled, regular calibrations, and accurate time-control—all these are important to any ion-measuring apparatus with which observations of highest accuracy and worth are to be made.

V. NUCLEI-COUNTERS

Large ions in the atmosphere are generally considered to be salt-crystals and pollution-particles of various kinds which either have come into the atmosphere already charged or have acquired charges by combining with small ions. Not all the salt-crystals and pollution-particles in the air are charged, and it is a matter of some importance to determine what part the uncharged particles play in the ion-equilibrium of the atmosphere.

More than 50 years ago John Aitken devised an instrument for counting the number of particles in the atmosphere which act as centers or nuclei for condensation of moisture [552]. Aitken called the particles "dust-particles" and his instrument the dust-counter, but, since his particles are not dust-particles as we know them, his particles are now called, to avoid confusion, condensation-nuclei and his small portable counter the Aitken pocket nuclei-counter. It and details are shown in Figure 19. A shallow circular receiver, *R*, connects through a three-way cock, *K*, with a piston-chamber, *P*, when the cock is set as shown. The cock, *K*, when turned 90°, connects the receiver to the outer air, while at the same time the piston-chamber is, by a separate orifice, also connected to the outer air. The volume of the receiver is a few cc and the piston-chamber about one-third that of the receiver when the piston is down at full stroke. Hence, the air in the receiver may be expanded about 30 per cent by a full piston-stroke.

The air in the receiver is kept saturated by a moistened disk of blotting paper, mounted on a loose disk within the receiver. When the counter is shaken, the disk mixes the air. In the bottom of the receiver is a glass window divided into millimeter-squares for a counting-stage, and on the receiver-cover is mounted an eyepiece, *M*. Light is directed into the receiver by an adjustable mirror mounted below the receiver on the piston-tube. To move the piston the operator uses the knurled collar which slides on the tube, *G*. When the piston is pulled down sharply, moisture in the receiver will condense on the nuclei present and make the latter readily visible through the low-power eyepiece as they fall on the counting-stage. It is always assumed that nuclei once deposited are never returned to the air and recounted, and the functioning of the counter indicates that such an assumption is justified.

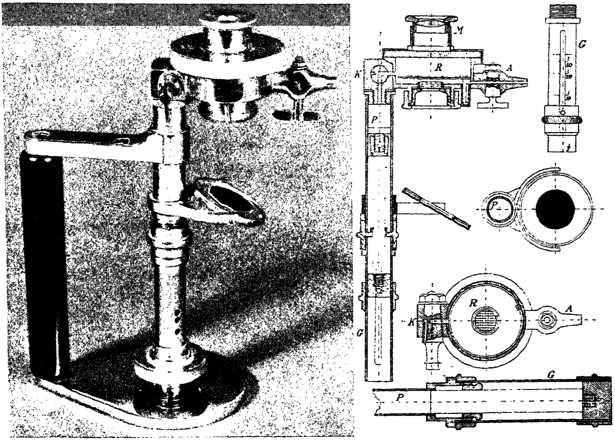


FIG. 19.—General view and detail sketches of Aitken pocket nuclei-counter.

On the side of the tube, *G*, are marked settings of $\frac{1}{5}$, $\frac{1}{10}$, $\frac{1}{20}$, and $\frac{1}{50}$, and when the knurled collar is placed with its bottom edge coincident with one of the settings the space above the piston-head is supposed to be $\frac{1}{5}$, $\frac{1}{10}$, etc., of the volume of the receiver. In the original Aitken counter this was not the case, nor is it true for more recently constructed instruments, as has been shown by Wait [585] in his study of seven counters constructed in the United States and Germany from Aitken's specifications. For some of the counters tested, the settings actually represented volumes of $\frac{1}{7}$, $\frac{1}{13}$, $\frac{1}{25}$, and $\frac{1}{60}$.

The use of the counter involves several systematic operations including initially clearing all nuclei from the receiver, next introducing a certain proportion of outside air, then mixing the air thoroughly, and finally expanding it enough times to insure the deposit of all nuclei from the air, at the same time counting all the droplets that fall on a chosen square in all the expansions.

To clear all nuclei from the receiver, the cock, *A*, is closed and cock, *K*, set as shown in Figure 19, after which repeated strokes of the piston are made until no more particles fall on the counting-stage. The piston is then set to one of the settings on tube, *G*, and the cock, *K*, turned 90°, permitting outside air to enter the receiver to equalize the pressure inside and outside. At the same turning of the cock, the piston-chamber is connected to the outside air and it is next exhausted into the outside air by bringing the piston to its highest position. The cock, *K*, is then restored to its first position, connecting the receiver with the piston-chamber. The counter is now shaken to stir the air in the receiver, the mirror is adjusted for best illumination of the counting-stage, and the piston is smartly pulled down for its full stroke. With the expansion thus produced, numerous droplets will appear and fall to the stage, where the number falling on a given square must be counted. The counting must be done very quickly as the droplets evaporate in a second or two.

The piston is then returned to its highest position, after which a second expansion is made. The droplets will in general be fewer on this expansion, and by the fifth or sixth expansion only one or none at all may fall if the counter is not leaking. Usually no particles are left to fall after the fifth or sixth expansion.

For a satisfactory set of observations ten repetitions of the above-mentioned manipulations are generally made.

If for a given setting of the piston more than ten droplets are deposited on the chosen square on the first expansion, the observation should be discarded, the receiver cleared of nuclei, and a new setting of the piston representing a smaller proportion of polluted air should be adopted for the particular occasion. To count more than ten particles before some of them evaporate is very difficult, and the piston-setting should always be such as to keep the number deposited at any one expansion at some value smaller than ten per square mm.

Above the counting-stage the receiver is made just ten mm high, so that the particles counted on one square represent the number present in a vertical column of 0.01 cc volume. Hence, for a setting of $\frac{1}{50}$ corrected, say to $\frac{1}{60}$ for a particular instrument, if the particles counted are 8, 5, 2, 1, 1 for a total of 17 on five successive expansions in one nuclei-count, the number of nuclei per cc in the outer air is computed as $60 \times 100 \times 17 = 102{,}000$ particles. Similarly for a setting of $\frac{1}{5}$ corrected to $\frac{1}{7}$, if five expansions give 2, 1, 0, 0, 0 for a total of three, the number of nuclei per cc is 2,100.

Since the supersaturation in the Aitken pocket nuclei-counter is a matter now of some sixfold, small ions in the atmosphere may join with the large ions and condensation-nuclei in acting as centers for formation of droplets, as the positive small ions require sixfold to sevenfold supersaturation and the negative small ions fourfold.

Aitken also constructed larger and more elaborate nuclei-counters [552], but the essential features do not differ from those of the pocket counter.

The Aitken nuclei-counter is not a recording-instrument, and no other instrument for recording condensation-nuclei has yet been devised. However, a considerable body of observational evidence exists, showing that the number of condensation-nuclei in any locality does affect the general electrical conditions of the atmosphere. Certainly, when nuclei are numerous, the potential-gradient of the atmosphere is greater and the conductivity less than when the nuclei are few. However, when the number of nuclei and the number of large ions in the atmosphere are studied at the same locality, it appears that nuclei-content and large-ion content do not change in a directly related manner [681], and to account for this difficulty it has been suggested that the Aitken counter does not count all the condensation-nuclei in the air on all occasions. As an alternative to the latter possibility it has been suggested that the nuclei change in size in relation to the amount of moisture in the air [696, 697]. Whatever the cause for the discrepancy, it is chiefly important here to remember that the Aitken counter takes no account of the electrical characteristics of the particles that enter it and, further, that its effectiveness must be based in some degree on the extent to which different particles are capable of acting as centers for condensation. Aitken showed that not all substances act equally well as centers of condensation [552]. Perhaps there are some large ions which do not act as condensation-nuclei and perhaps others around which are formed droplets too small to be seen with the low-power eyepiece of the Aitken counter. The Aitken nuclei-counter, important as it is for investigating the broader aspects of formation and destruction of ions, may not provide adequate data for the formulation of laws governing the more precise relationships between ions of various classes and the uncharged particles which affect ionic equilibrium.

For quantitative study of particles of dust and soot of such size as may be seen with a high-power microscope, the Owens jet dust-counter [574] and the Owens automatic pollution-filter [573] are much used. However, it is questionable whether the larger pollution-particles play a sufficient part in establishing or regulating the electrical conditions of the atmosphere to warrant the inclusion of these two instruments among the pieces of apparatus important in atmospheric-electric measurements.

VI. IONIZATION-APPARATUS

There has been no apparatus developed up to the present that will give absolute quantitative measure of the number of small ions produced in unit-volume in unit-time in the lower atmosphere by the ionizing agents present within a few meters of the Earth's surface. Various instruments have been devised [633] for the purpose, but with all of them certain allowances or adjustments of measurements must be made, and the final adjusted values can be taken as only approximate.

Such ionizing agencies as the photoelectric effect and the Lenard effect contribute to the ion-production near the Earth's surface only in exceptional cases, so that in general an ionization-apparatus must be designed for the study only of the radioactive ionizers and cosmic rays.

The study of the ionizing effect of radioactive substances in the atmosphere and of cosmic rays is usually made with some sort of ionization-chamber. The chamber is an air-tight container, usually cylindrical or spherical, which will hold perhaps 25 or 50 liters of air. Centrally located in the chamber is an insulated electrode or rod, the rod connecting directly to the fiber of some form of unifilar electrometer. With a potential across the rod and chamber or, in some cases, across the rod and an insulated shell fitting closely within the chamber, small ions produced by bombardment of the air-molecules by radioactive ionizers and by cosmic rays are collected on the central rod. From the deflection of the electrometer so produced the number of pairs of ions per cc per sec may be deduced. The method suffers from the fact that the ionizers bombard not only the air but the apparatus also so that secondary radiations are created within the vessel and these raise the rate of ion-production to a value greater than that for the outside air. Furthermore, radioactive substances embedded in the walls of the chamber add very considerably to the ionization in such an apparatus. The amount of ionization produced by secondary and wall radiations will depend to some extent on the character of the material composing the ionization-chamber, as well as upon the quantities of the different radiations—alpha, beta, and gamma—acting within the chamber. Cosmic rays passing through the walls of a chamber not protected by heavy shields of lead cause quite appreciable secondary radiations and thus augment the measured ionization.

The shielding effect of the walls of the ionization-chamber also introduces uncertainty in the measurements. Were the chamber-walls not present, some of the alpha particles in the air just outside the walls would then be ionizing the air just within the walls and an appreciable correction must be made for such a situation.

When the electrometer of an ionization-apparatus is arranged for photographic recording, comparisons of the rate of ion-production can be secured from hour to hour and day to day, and the characteristics of the variations in rate of ion-production determined even while absolute values are determined only approximately. Recording ionization-apparatus is a valuable adjunct in investigations where ion-counters and conductivity-instruments are being continuously operated.

Some of the familiar cosmic-ray meters [1146, 1183] are ionization-chambers, elaborate in various details, but conforming in essential features to the brief description given in an earlier paragraph. The chambers are, however, heavily shielded in lead of sufficient thickness to stop all radiations coming from near-by objects or from the radioactive products in the surrounding air, while permitting the very penetrating cosmic rays to enter.

Over the oceans, at a considerable distance from land, the radioactive ionizers are found only in negligible quantities, and cosmic rays are responsible for all the ion-production. Hence, cosmic-ray meters may be used over the oceans without shielding, and much information has been obtained in this way about ion-production over the oceans [527].

Over continental areas, radioactive ionizers are responsible for much greater ion-production than are cosmic rays. Among the more recent studies of ion-production over land areas may be mentioned the work of Hogg [641, 642].

His apparatus consists of an ionization-chamber of zinc in the form of a cylinder about 25 cm in radius and 25 cm high having a volume of 50 liters. The walls of the chamber are 0.4 mm thick. The inner electrode, two mm in diameter, is supported centrally in the base of the chamber by a shielded insulator. The electrode is connected by a fine shielded wire to a Wulf unifilar electrometer (sensitivity 150 divisions per volt), and the latter is protected from sudden temperature-changes by being enclosed in felt and surrounded by an earthed shield of aluminum. The electrometer is arranged for photographic recording. The pump used to fill the chamber for the tests of ion-production supplies air at the rate of eight liters per minute, the air being supplied to the apparatus through a short length of glass tubing protruding through the wall of the laboratory into the free atmosphere. By means of a program-machine controlled by a pendulum master-clock, various automatic relays and contacts bring about a cycle of several changes every hour.

First, air is drawn through the chamber for ten minutes, after which the chamber is sealed off. Then the increase of potential of the electrometer is measured during 15 minutes while a potential of +6 volts is applied to the chamber. For three additional periods of ten minutes each, the increase of potential of the electrometer is measured when +20, +40, and +100 volts, respectively, are applied to the chamber. With intermediate periods of a minute or two for automatic earthing of the electrometer-fiber, the cycle of operation occupies a full hour and is repeated from hour to hour. The potentials applied are not great enough to produce saturation-current in the apparatus, the saturation-potential being arrived at by a method of extrapolation. Besides saturation-potential, there are required the electrostatic capacity of the chamber, its volume, the period of observation in sec, and the value of the electronic charge, in order to derive the rate of small-ion production within the chamber. The value so found represents the ion-production due to all possible sources, including: Radioactive gases and suspensoids in the free air (atmospheric radiation); radioactive radiations from the soil (soil-radiation); cosmic radiations; secondary and wall radiations from the apparatus itself; and radiations from the observing building. The ion-production from the radioactive ionizers in the free air will be recorded at lower than true value, due to the shielding-effect of the walls of the chamber, and must be increased by several per cent.

If now air is drawn into the apparatus through a cotton-wool filter and is allowed to stand for a month before observations are made, the observed rate of ion-production is lower than before since the atmospheric radiation is not now contributing importantly.

In a further test, if the apparatus containing air drawn in a month earlier is moved out-of-doors, the radiations from the building will no longer contribute to the measured rate of ion-production.

Finally, with the apparatus again containing air admitted to the chamber weeks earlier, set over a reservoir of water a few meters deep, the Earth radiation will be cut off, leaving only the effect of cosmic rays and of the secondary and wall radiations from the apparatus itself. With the effect of cosmic rays known from other work, the effect of the instrument itself upon the thing it is measuring is finally deduced. Hogg found the secondary and wall radiations from the apparatus itself, together with the radiations from the laboratory building, to account for about 20 per cent of the ionization measured in air newly admitted to the ionization-chamber.

An ionization-apparatus designed by Wait utilizes cellophane of 0.03-mm thickness as the wall of the ionization-chamber. Designed as a recording instrument to study diurnal variation in the rate of small-ion production, the apparatus has given some results of special interest showing abnormally high rates of ion-production during thunder-storms [782].

The apparatus is shown diagrammatically in Figure 20. The chamber consists of a cylinder of brass screen of six-mm mesh, covered with a single layer of cellophane. The stopping-power of the cellophane for alpha particles is equal to one and one-half cm of air. The chamber is made air-tight, and the air within it, when the final sealing is done, remains there until the cellophane requires replacing. The cellophane remains intact for periods of many months.

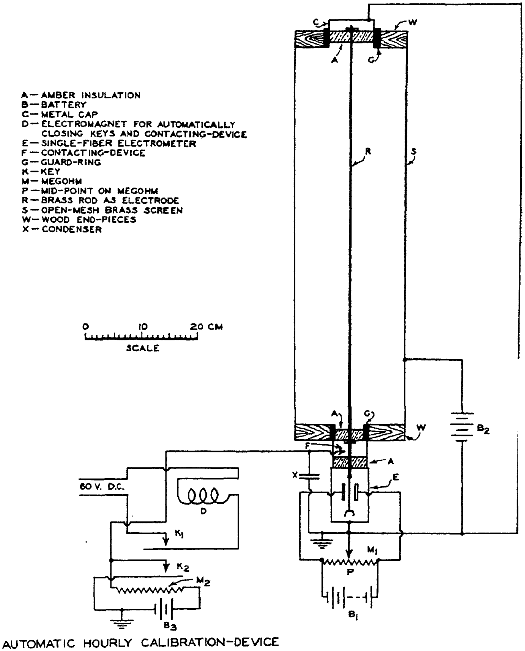


Fig. 20.—Schematic diagram of apparatus for measuring the rate of small-ion production.

An electric field maintained between an insulated central rod of brass and the screen causes ions of one sign to collect on the rod. A unifilar electrometer connected to the rod measures the charge accumulated, to indicate the rate of ion-production. The accumulation of charge is allowed to continue for 54 minutes of each hour, after which the rod is discharged and the electrometer calibrated in the remaining six minutes of the hour. The cycle of operations is automatically performed. The deflections of the electrometer-fiber during regular recording and during calibration are photographically recorded.

With this apparatus, as with other ionization-instruments, the absolute value of the rate of ion-production for any given time can only be approximated. Alpha particles contribute 50 per cent or more to the small-ion production in the free atmosphere, but in the cellophane-chamber their contribution must be estimated. After the chamber has been sealed off a few days, alpha particles are no longer uniformly distributed throughout the air of the chamber and those which do get in through the cellophane-wall are slowed down in the process so that they travel, at most, only two or three cm from the wall before they become inactive. Many of the alpha particles outside the chamber, which might have acted on the particular volume of air confined in the chamber had the cellophane not been there, are stopped from doing so. The ionization by alpha particles is probably 50 per cent too low as measured with the cellophane-chamber. The radiations from the soil, chiefly gamma rays, and the cosmic rays presumably produce ions in the confined air just as well as in the free atmosphere, but they also cause secondary radiations from the wall of the chamber, and the ions produced by the secondary radiations and by radiations from radioactive matter in the screen-wall of the chamber must be subtracted out in the final computations of the rate of ion-production. From measurements with the apparatus it appears that the ionization produced by the secondary and wall radiations is about one or possibly two ion-pairs per cc per sec.

In Figure 20 the battery, B_2, is shown with its positive terminal connected to the wall of the chamber and its negative terminal to the earthed electrometer-case and to the mid-point of the resistance, M_1. If the negative terminal of B_2 is connected instead to the wall of the chamber, the arrangement is not satisfactory as the ionization within the chamber is augmented by the radiations from the positively charged radioactive substances which have been drawn to the chamber-wall from the adjacent air.

For continued recording with the apparatus the best arrangement has been found to be to change the earth-connection from the electrometer-case and mid-point of M_1 to the chamber-wall and positive terminal of the battery, B_2. A potential-difference of 90 volts between the chamber-wall and central rod is sufficient for saturation.

With the electrostatic capacity of the apparatus (chamber and electrometer) 15.3 cm, the volume of the chamber 23 liters, the charge per ion 4.77×10^{-10} ESU., the period of recording 3,240 sec (54 minutes), the ion-production per cc per sec is found from the equation $I = 1.44v$, where v is the change in potential, expressed in volts, of the central rod during the 54-minute period. If, for example, the electrometer deflects 20 mm in the 54-minute period and the sensitivity of the electrometer is four mm per volt, then 7.2 ion-pairs are produced per cc per sec in the chamber. How closely the value of 7.2 ion-pairs may represent the true rate of ion-production in the air in the vicinity of the apparatus, when that value is obtained, is not known. It is thought to be fairly close, on the basis that the rate of ion-production within the chamber by alpha particles is too small by perhaps one or two ion-pairs, while the secondary and wall radiations are thought to make the measured rate of production too large by one or two ion-pairs.

Since those ionization-measurements which have been made show that there is a quite large diurnal change in rate of ion-production and other changes in rate associated with meteorological and climatic variations at any particular observing-station, it is essential for proper study of atmospheric electricity to measure not only potential-gradient, conductivity, and ion-content of the air but also the rate at which small ions are produced.

VII. SPACE-CHARGE APPARATUS

It is well known that the potential-gradient of the atmosphere falls off with elevation above the Earth's surface, and to account for this falling off there is assumed a positive space-charge in the atmosphere. That a positive space-charge does ordinarily exist near the Earth's surface has been shown by several different experiments, but no long series of simultaneous, continuously recorded measurements of both space-charge and potential-gradient was made before that of Brown in 1929 [599]. Very marked and sudden changes in space-charge were observed by him, and such effects must be considered in studies of atmospheric electricity.

The apparatus used by Brown is shown schematically in Figure 21. A metal cylinder supported in an amber insulator is tightly packed with the finest grade of steel wool, the quantity of steel wool being sufficient to filter out all the ions in the air drawn through. The collecting-cylinder is housed in an earthed case, and an intake tube projects through the wall of the observing-building into the free atmosphere.

The electrostatic capacity of the collector-system of the particular dimensions used is 66.7 cm. The electrometer is of the Dolezalek type, one pair of quadrants being earthed and the other pair being connected to the collecting-cylinder. The electrometer-sensitivity is 62 mm per volt on the photographic paper placed 60 cm distant. The air-pump is run at constant speed by an induction-motor and draws air through the steel-wool filter at a constant rate of 3.2 cubic meters per hour, as indicated by a gasometer. The drum on which the photographic paper is mounted is rotated once a day by a telechron motor. The motor also operates the grounding-key once each hour and records the time. The preponderance of positive over negative electrified particles in the air, or of negative over positive, is indicated by the direction and magnitude of the electrometer-deflection. With this apparatus, space-charge values from 0.01 to 0.50 ESU per cubic meter have been conveniently measured.

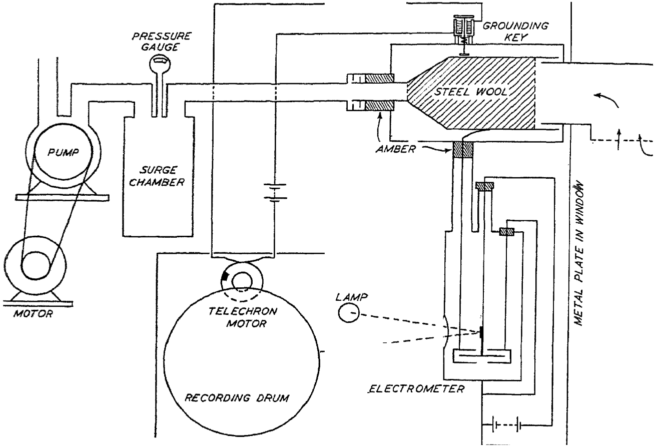


FIG. 21.—Schematic diagram of Brown's space-charge apparatus.

VIII. AIR-EARTH CURRENT DETERMINATIONS

Values of air-earth current may be derived directly or indirectly. In the direct method there is determined the electric charge accumulated during a certain time-interval on the Wilson test-plate shown in Figures 7 and 8. From observation of the electrometer-deflection (in terms of potential) when the test-plate is first exposed and again just after the plate is covered following a definite period of exposure, both the potential-gradient and air-earth current may be obtained.

In the indirect method, the sum of the measured positive and negative electrical conductivities of the air is multiplied by the potential-gradient, the measurements, of course, all being made at the same site. The indirect method is most suitable for determining the air-earth current during fair-weather conditions when the potential-gradient is maintained at fairly steady values for long intervals and the conductivity is very little disturbed.

IX. AUXILIARY APPARATUS

To interpret best atmospheric-electric measurements, meterological conditions at any observing-station should be recorded as completely as possible. Important auxiliary recording-instruments include the barograph, thermograph, hygrograph, anemograph, and pluviometer. For other environmental conditions, visual observations and notes on weather must take the place of apparatus, and items which assist greatly in interpretations of unusual atmospheric-electric observations include the kind and amount of cloud throughout each day, prevalence of haze or smoke or dust in the atmosphere, when snow is on the ground (how deep it is and how long it remains), and any special details relating to residential or industrial activity which might conceivably affect the electricity of the atmosphere.

CHAPTER VI

EARTH-CURRENTS

W. J. Rooney

Department of Terrestrial Magnetism; Carnegie Institution of Washington

I. INTRODUCTION

The term "earth-currents" in a geophysical sense should be construed as excluding not only all artificial or man-made flow of electricity like that due to leakage from power-systems but also at least some natural currents which are purely local in character. In this latter category fall the currents generated by chemical processes which are associated with certain minerals, small currents due to temperature-differences in the Earth, and surges caused by lightning-discharges. Of these the first two are so small in magnitude, and the last so brief in duration, that they are of relatively minor importance. Electric currents generated when a portion of the Earth moves in relation to its magnetic field, for example, those arising from strong tides or large oceanic currents, are also local in character. However, since they are associated with the magnetic field, they cannot be completely dissociated from the study of earth-currents, even though consideration of them may extend no further than is necessary to subtract their effects from the records to secure an undistorted picture. However, such currents are probably so small and their distribution is so restricted that they may be neglected in a general discussion such as this.

If all these local currents—artificial and natural alike—are allowed for, there is still found positive evidence of the existence of electric currents circulating in the crust of the Earth. And it is further found that these currents constitute a world-wide system differing markedly from place to place and subject both to irregular and spasmodic, and to regular and periodic, variations in intensity and direction. Both the regular variations and the disturbances show a consistent relationship to the changes noted in other cosmic phenomena, notably the Earth's magnetic field, the aurora, and solar activity. It is this type of current-flow which for convenience is referred to as "earth-currents."

II. HISTORICAL

Investigations dealing with earth-currents are almost as old as the science of electricity itself. Sir Humphrey Davy, in 1821, was probably the first to suggest their existence, and Faraday, in 1831, although unsuccessful in his attempts to detect them with the primitive equipment at his disposal, was nevertheless convinced that they must exist when he discovered the principle of electromagnetic induction. Barlow [1387], in 1847, from his measurements on English telegraph-lines, was the first to obtain convincing evidence that natural electric currents do flow in the crust of the Earth. Following Barlow's work a number of other investigations took place most of which were made on telegraph-lines and chiefly at times of disturbances. Nevertheless, these fragmentary records, which dealt only with the irregular fluctuations found under storm-conditions, soon showed a connection between the earth-current disturbances and magnetic storms and auroras. Not long afterward it was noted that the periods of maximum earth-current disturbance corresponded to those of maximum sunspot-frequency.

Systematic, continuous observations of the phenomenon lagged behind the intermittent recording of disturbances and also behind the more systematic investigation of allied phenomena. This was partly due to the difficulties encountered in securing satisfactory records of the normal earth-current activity because of the masking effects of extraneous potentials always present and arising from the chemical and physical conditions at the electrodes or points of contact with the ground. The influence of these contact-potentials on the records is the greater the shorter the lines used for the measurements, and the tendency is always to use the shortest lines possible for reasons of economy. Of even more moment than the difficulties themselves in retarding the advancement of earth-current work, in recent times at least, has been a lack of appreciation of their influence, on the part of some investigators, and a consequent failure to allow for and eliminate from the results the effects of contact-potentials. The net result has been that the often contradictory and sometimes patently absurd conclusions reached in those cases led to a rather widespread disbelief in the practicability of such measurements and in the value of the results. Despite all this a number of series of observations of unquestioned value were obtained during the last third of the past century. Notable among them are those at Greenwich [1386], 1865–67, continued with a readjusted layout of lines until the early nineties; at Berlin, 1883–91, the results of which are covered in Weinstein's comprehensive report [896]; and at Parc St. Maur, Paris, also in the early nineties. The advent and rapid expansion of direct-current power-systems, particularly railways, toward the close of the nineteenth century put a further check on the systematic observations. It was the interference by strays from electric railways which caused the abandonment of the earth-current programs at Greenwich and Paris, and for this same reason measurements of this nature are now quite out of the question in densely populated urban regions.

Continuous registration was revived in 1910 at the Ebro Observatory, Tortosa, Spain [1397, 1400], where the measurements were continued to 1938. The Ebro records constitute the longest series of nearly continuous recording. In addition to the equipment at Ebro, installations for the systematic observation of earth-currents have been operated at the two magnetic observatories of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington, at Watheroo, Western Australia [871, 876], since 1923, and at Huancayo, Peru [877], since late in 1926. Another project for earth-current measurements was initiated in 1931 at Tucson, Arizona, where the work is being carried on cooperatively by the Department of Terrestrial Magnetism, the United States Coast and Geodetic Survey, and the American Telephone and Telegraph Company [888, 1394]. Besides the work at these permanent observatories, several temporary series of observations have been secured. Sets of observations ranging in duration from one month to three years or more have been secured by the American Telephone and Telegraph Company on lines in the eastern and mid-western states. In connection with the Second International Polar Year, 1932–33, continuous records were obtained for 18 months at the United States station at College-Fairbanks, Alaska [892], and about a year's record at the Canadian station at Chesterfield Inlet [866]. Earth-current measurements at Sodankylä, Finland, and at Tromsö, Norway, were also included in the Polar-Year program, and a considerable record has been obtained by Stenquist [1399] on Swedish telegraph-lines. Reports of similar programs either in prospect or under way at Alibag, India, and in South America and Japan have also been received.

The progress of the investigations of earth-currents prior to the installation at Ebro with a summary of the results and an extensive bibliography was given by Burbank [863] in 1905. A general review in which the results and underlying theory are brought up to date was made by Gish [872] in 1931. More specific references to recent work will be found on pages 744–746.

III. MEASUREMENTS

(1) General

To determine completely the current-density in any portion of the Earth's crust it is necessary to know both the potential-gradient and the specific conductivity or resistivity of the region. Nevertheless, most determinations of earth-currents have consisted solely of measurements of the former, and the results are given usually in mv per km and not in terms of current-density. So the potential-measurements will be considered first. Superficially the potential-measurement is simplicity itself.

The usual procedure has been to select a number of points, three as a minimum, where ground-connections are available or readily made, or where the connection to detecting devices is provided by existing lines, and to record either continuously or intermittently the potentials between each pair of points. From the records so obtained and the known lengths and directions of the lines, the magnitude and direction of the potential are obtained.

For most studies of correlation, such as with the variations of the magnetic elements, the records are in the most convenient form when expressed in terms of the geographical coordinates. Hence, where special lines are installed for systematic recording it simplifies the work of reduction if the two pairs of points are placed on due west-east and south-north lines, respectively, since N, the northward component, and E, the eastward component, are then obtained directly from the record. The magnitude of the actual potential-gradient and its azimuth are readily calculated since

$$R = \sqrt{E^2 + N^2} \qquad \text{and} \qquad \tan \alpha_R = N/E$$

where α_R is the angle which R makes with the X-axis or west-east line.

A particular orientation of the lines is not essential to the measurement, however, and any two lines of different azimuths can be used if conditions preclude the north and east rectangular arrangement. It should be noted that the true eastward and northward components are not simply the projections on those axes of the observed rates of change of potential along non-axial lines. To obtain them the observed gradients must be resolved along the rectangular axes. This resolution when carried through [871] gives the following expressions for the geographical components:

$$E = (E' \sin \alpha_2 - N' \sin \alpha_1)/\sin (\alpha_2 - \alpha_1)$$
$$N = (N' \cos \alpha_1 - E' \cos \alpha_2)/\sin (\alpha_2 - \alpha_1)$$

where E' = the intensity-component along the more easterly line, N' = the intensity-component along the more northerly line, α_1 = the angle made by the easterly line with a true west-east line, taken in a counter-clockwise direction from the west-east line, and α_2 = the angle made by the northerly line with a true west-east line taken in the same sense.

The magnitude and direction of the actual potential-gradient could also be expressed in terms of the observed quantities and the azimuths of the lines, but the data are more conveniently used in the form given here, and once the northward and eastward components are known the resultant is readily determined from them.

(2) ELECTRODES

Most of the difficulties encountered in the measurement of earth-currents can be traced to the electrodes. It is practically impossible to make contact with two points in the ground without some potential existing between the two conductors used to make the contact. This is true no matter how much care is taken to make the electrodes as nearly as possible identical chemically and physically and to equalize the conditions in the soil in which they are set. In all such measurements, therefore, allowance must be made for these contact-potentials. Furthermore, the differences in potential between pairs of electrodes due to electrochemical activity are found to be by no means constant but to vary over rather wide limits, chiefly as a result of changes in the concentration of the solutions surrounding the electrodes and to a lesser degree because of physical changes such as variations of temperature. Consequently, earth-current measurements are very liable to error from this source.

In an effort to minimize the spurious effects arising at the electrodes, considerable variety of electrode-material has been tried out both in actual use in the field and in the laboratory [881]. Of the metallic electrodes used, lead, iron, and possibly cadmium seem to be the best. Reversible electrodes, such as copper dipping into copper-sulphate solution, or zinc in a solution of zinc-sulphate, the solution making contact to the ground through a porous container, have also been used to considerable extent. The reversible electrodes tend to show a somewhat smaller difference in potential than do the metallic ones and the differences remain fairly constant as long as the electrodes are properly maintained. However, in a permanent installation proper maintenance is a difficult matter and the use of solutions is apt to result in a gradual change in the conductivity of the soil in their vicinity due to leaching of the solutions into the ground. As a result, the character of the potential-field near-by may be modified to a marked degree as time passes. Reversible electrodes are also rather sensitive to changes in temperature. Although this is a disadvantage they share with the metallic electrodes, it is a matter of more moment in the case of the reversible ones, since they must be located so as to be accessible in order that solution may be added from time to time if the advantages of lower and more constant potentials are to be realized. So, although the metallic electrodes are theoretically inferior, it is probable that when, carefully installed, they prove the more satisfactory in the long run.

The electrode-requirements for satisfactory measurements are: (1) Contact-resistance which is low in comparison with the total circuit-resistance and as constant as possible; (2) a minimum of electrochemical activity at the electrode, and, more particularly, a minimum variation in this activity so that the contact-potentials shall be as low as feasible and shall undergo as little variation as can be effected; and (3) adequate insulation of the lead-in wires joining the electrodes to the connecting lines.

The first requirement—low and constant contact-resistance—is particularly important when the recording instrument is of the galvanometer-type, since the resistance of the recording circuit, exclusive of that of the galvanometer and control-resistances used with it, is to a large part determined by the contact-resistances. If, for instance, the contact-resistances should happen to equal the resistance of the remainder of the circuit, the potential between the outer ends—that is, the line-ends—of the two electrodes will be only half that existing between two points just inside them and a change of ten per cent in the contact-resistances would mean a change of five per cent in the deflection corresponding to a given ground-potential. Under these conditions the evaluation of the records would involve an accurate knowledge of the contact-resistances at all times, an obviously impracticable situation. If, on the other hand, the contact-resistances are small in comparison with the total circuit-resistance, say one-half of one per cent or so, the correction for the IR-drop at the electrodes becomes negligible and the contact-resistances may vary over a fairly wide range without affecting the scale-value. In this case it is not necessary to know the value of the contact-resistances with any great accuracy.

When a common electrode is used in the determination of two or more components of earth-current flow by galvanometer-measurement of potentials between it and other electrodes, it is particularly important that the contact-resistance of the common electrode be made small in comparison with that of the galvanometer-units. If the electrode-resistance is comparable with that of the galvanometers, an appreciable portion of the current, instead of flowing from the common electrode through one galvanometer to a specified outer electrode, will be shunted through the other galvanometers to one or more of the other outer electrodes and this "cross-action" will quite effectively destroy the value of the several records.

Where a null method of potential-measurement is used, the contact-resistances do not affect the records directly, but even then low contact-resistances are desirable. If they are permitted to become large, the balancing mechanism will be sluggish and tend to introduce error in the records because of failure to obtain a complete balance in the time allotted, or because of what might be termed "back-lash," a fairly constant difference in the balance-position when it is approached from above or below. And finally, regardless of the type of recording instrument, the effects of any insulation-leaks, which may occur at any point of the system, will be exaggerated by high contact-resistances at the electrodes.

The contact-resistances of electrodes depend primarily on the resistivity of the soil in which they are set. This varies widely with the character and condition of the soil. The resistivity of moist clay may be less than 100 ohm-cm while measurements of the resistivity of coarse, dry sand have shown values as high as 5×10^6 ohm-cm. If the soil-resistivity is known, the contact-resistance can be readily calculated for electrodes of symmetrical shape. The contact-resistance decreases as the area of the surface of the electrode increases, but, since most of it consists of the resistance offered by the soil near the earth-plate, a solid surface of large area is not the best from the standpoint of economy or ease of installation. An open grid of conducting material providing a number of parallel paths of flow into the adjacent ground is much more effective for a given amount of conductor used. In ordinary soils, clays, alluvia, disintegrated sedimentaries, and the like, which have resistivities under 10^4 ohm-cm, electrode contact-resistances of 100 ohms or less can be secured with grid-electrodes of moderate size. Seventy-five to 100 feet of pure lead wire built into a horizontal grid covering an area of 25 to 40 square yards should prove sufficient in soils of such character. An electrode of this size and type set in clay at the Polar-Year Station at College-Fairbanks [892] reached a maximum contact-resistance of only 120 ohms during the arctic winter when the temperature ranged from −20° to −30°C for three months or more and the ground must have been fairly solidly frozen. Its resistance during the summer was under 50 ohms. A similar electrode in the same installation, set in a peat-bog, ranged from about 20 ohms in the summer to a little over 400 ohms in the winter. Two other electrodes, set in swampy tundra so that they were effectively water-electrodes, had contact-resistances between 100 and 200 ohms during the summer, but these increased tremendously during the freeze-up, one reaching a value of 54,000 ohms toward the end of the winter. Since conditions as severe as those at this station are seldom encountered, it is the values in summer which are of most importance. Somewhat larger electrodes of the same type in use for a number of years at Huancayo (set in semiconsolidated conglomerate) and at Tucson (in fine alluvium) have remained well under 100 ohms in contact-resistance. At Watheroo electrodes of the lead-grid type proved somewhat unsatisfactory when set in porous sand. During the long dry seasons there the contact-resistances reached values of some thousands of ohms in some instances. The electrodes were relocated in clay and have remained under 50 ohms in contact-resistance even during the dry seasons since the change was made. If sand, coarse gravel, and rock are avoided in choosing sites for the electrodes, the lead-grid type can be counted on to have a satisfactory contact-resistance.

The second requirement, namely, that the electrochemical activity at the electrodes shall be small and unvarying, cannot be so readily guaranteed since it is quite out of the question to control the chemical composition of the soil or to prevent gradual changes in the moisture-content and in the concentration of solutions in it. Aside from choosing electrode-material which is of low activity and selecting sites which are as nearly alike as possible and are the least likely to be subject to wide variations in moisture-content, there is not much that can be done in this respect. If it were possible to guarantee that the contact-potentials in a given instance should be small in comparison with those due to earth-current flow, the effect of variations in them would again be of minor importance. Since, however, some contact-potential is sure to exist, and since its magnitude is largely beyond control, this factor can never be neglected in evaluating the records. In order that proper allowance can be made for the contact-potentials, it is essential that such variations as they undergo either be small or else be known with considerable accuracy. Accurate knowledge of the variations is again a matter of little feasibility as they are inextricably mixed up with the earth-current variations. Hence, the only hope for successful recording lies in minimizing the variations as much as possible. So it follows that, whereas the important point with reference to the contact-resistances of electrodes is their magnitude, the emphasis in the case of the contact-potentials must be placed on securing a minimum of variation in them. Fortunately the same factors which make for low and steady contact-resistance, chief of which is a compact soil deep enough to be free from great variations in moisture, also tend to make the contact-potentials fairly steady, even though they may be large if the type of soil differs at the two electrodes of a pair.

Even under the best of conditions slow changes in the contact-potentials due to seasonal variations in moisture must be expected. These usually appear in the records as gradual changes in the daily mean values. They can be distinguished quite readily from earth-current variations and consequently are not a serious menace to the accuracy of the records. Besides such slow changes, electrodes which are not wisely located and carefully installed will be subject to abrupt short-period changes in contact-potential, some of which may acquire a diurnal period and which are readily confused with the variations due to earth-currents. It is this type of change which is particularly to be avoided. These short-period variations in contact-potential are chiefly due to two things, namely, rapid changes in moisture-content occurring during or after rainfall in porous soil at an exposed site, and changes due to variation of temperature in the ground near the surface. As far as rapid moisture-changes are concerned, low points—particularly low points in the bed-rock profile—will generally prove more satisfactory electrode-sites than exposed ridges, since natural drainage tends to maintain constant moisture-conditions at low points and variable ones at high points. Changes due to variation of temperature can be eliminated by placing the electrodes at depths beyond that at which any appreciable changes of temperature occur. Deep electrodes are also less liable to mechanical disturbance, and at any place where measurements are to be made for a considerable length of time the electrodes should be set at a depth of at least four to six feet.

The third requirement for satisfactory electrode-performance—adequate insulation of the leads joining the electrodes to the lines—is, strictly speaking, not a feature of the electrodes at all but of the lines and of the insulation of the system as a whole. It is included in the discussion of the electrodes because it is a factor which must be taken care of when the electrodes are installed and which, if neglected, can entirely nullify the efforts spent in installing electrodes quite satisfactory in every other respect. It is probably safe to say that at least 90 per cent of the difficulties encountered in obtaining satisfactory electrode-performance are due to this factor alone.

The connection from line to electrode will normally be made by means of ordinary copper wire. If this wire is not very efficiently insulated, we have, instead of a simple electrode of the selected material, a compound electrode with parallel copper-to-ground and lead-to-ground contacts, each part having different contact-potentials and different contact-resistances. The potentials recorded with such an electrode will be the unpredictable resultant of those due to the two sections and will depend on about six variable factors. Moreover, since the connector must pass through the critical surface-layer of earth where conditions of temperature and moisture may vary from day to day or hour to hour, it is almost certain that the resultant recorded potentials will not be free from short-period fluctuations which will surely confuse, and may completely mask, the variations due to the flow of earth-currents. Consequently the most careful attention should be given to the insulation of the connector and of the splice joining it to the electrode proper. Heavy rubber insulation impervious to moisture, similar to that on the best grade "Tyrex" cable, is absolutely essential. When the installation is to be used for a long time, an outer shield should also be provided to prevent abrasion or other damage to the insulation.

The magnitude of the error due to faulty insulation can be shown to be proportional to the ratio of the electrode contact-resistance to the insulation-resistance. Consequently if the former is kept low, the error from this source is lessened. With electrode-resistances of 100 ohms or less an insulation-resistance of five megohms for the connector should suffice. If the contact-resistance is as high as 1,000 ohms, the insulation-resistance should be ten times as great. These values—5 to 50 megohms—for the insulation-resistance of the connectors, which are comparatively short lengths of wire, may appear rather easy of attainment. Securing initial values as high as these does not offer any particular difficulty but it will be found that they will not be maintained over a period of years unless the installation is made with the utmost care.

The necessity for guarding against insulation-leaks in the connectors is all the more urgent because its effects are insidious. It is extremely difficult to determine whether a given variation noted in the records is due to this cause since the electrode-potentials and the leakage-potentials cannot be isolated. For this reason inadequacy of insulation of connectors can usually be demonstrated only by inference based on the differences between records in which its influence is suspected and those secured with assuredly adequate insulation, or by comparison of duplicate independent records from a number of electrode-pairs. Finally, in order to remedy deficiencies in the insulation of the connectors it is usually necessary to uncover the electrode and replace the connector. All these considerations emphasize the desirability of careful initial installation.

(3) RECORDING INSTRUMENTS

Either galvanometers or potentiometers can be used to measure the earth-potentials. The former have been used in practically all important series of systematic observations except those at Watheroo and Huancayo where multiple-range recording potentiometers are in use instead. The potentiometer-installation has the advantage that, since the potentials are measured by a compensation-method and no current is flowing in the system under balanced conditions, there is less likelihood of errors due to polarization or to changes in the contact-resistances of the electrodes. Another advantage of the recording potentiometer is that the recorded points (printed by a stamp-wheel) are immediately available for reference and the trend of the variations can be determined at any time without waiting for development of photographic records. Necessary changes in range or sensitivity can consequently be made with less likelihood of loss of record. The instrument can also be set up in any convenient room, neither darkness nor close temperature-control being required for its operation.

The intermittent record given by the recording potentiometer is quite satisfactory for the determination of diurnal variation and other changes with periods of several minutes to an hour or more. It is not, however, suited to the study of short-period disturbances. Hence, for comparison with records of magnetic disturbances or for correlation-studies, such as with auroras or with the results of ionospheric investigations, the potentiometer-records are at a distinct disadvantage. The potentiometer-installation is less flexible than the galvanometer-unit with regard to changing the sensitivity. Sometimes changes in the lengths of line or distance between electrodes have been found necessary for this reason.

The first cost of the potentiometer is also considerably greater than that of galvanometers and this fact, together with the requirements for power to operate the balancing and recording mechanism, precludes its use in many cases. A detailed description of the potentiometer-installation at Watheroo, which applies also to that at Huancayo, has been given by Gish [871].

Under the heading "galvanometers" may be included recording milliammeters or millivoltmeters which have been used in some instances. Except on very long lines, however, instruments of this type are out of the question because, when they are sufficiently sensitive to record the potentials on short lines, their internal resistances are so low in comparison with the resistance of the external circuit that the records are apt to be seriously affected by variations in the contact-resistances at the electrodes. Even when used on long lines they rarely will offer a sufficient factor of safety in this respect to insure direct and reliable records. Their usefulness is consequently limited to special cases where the distance between electrodes is great and photographic registration is for some reason not possible or desirable.

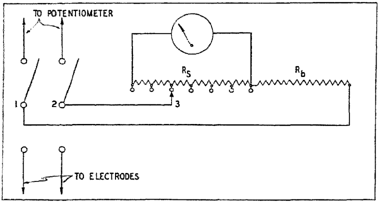


FIG. 1.—Simple galvanometer-circuit for earth-current observations.

Probably the best all-round instrument for the measurement of earth-current potentials is a D'Arsonval-type galvanometer used with a photographic recorder, provided the characteristics of the instrument chosen are such as fit the particular conditions of the installation. Best results are obtained by using galvanometers which have a high critical damping-resistance and a current-sensitivity considerably higher than would be required to obtain full scale-deflection when the instrument is connected directly across the earthed points. In use, a high resistance is placed in series with the galvanometer and its shunt, the circuit being arranged as shown in Figures 1 and 2. This arrangement not only minimizes the effects of polarization at the electrodes but also, by virtue of the large constant series-resistance, offers a number of other advantages to the ease and accuracy of recording. These advantages may be enumerated as follows:

(*a*) Variations in the external circuit-resistance do not affect the registration. On short lines the external circuit-resistance consists chiefly of the contact-resistances at the electrodes, and even on long lines these are a large percentage of the total resistance. The importance of insuring that they constitute only a small fraction of the total circuit-resistance was shown in the discussion of the electrodes.

(*b*) The electrode-resistances and the resistance of the connecting lines need not be known except as to order of magnitude. Hence, the expenditure of time and trouble in frequent redeterminations of these resistances is eliminated.

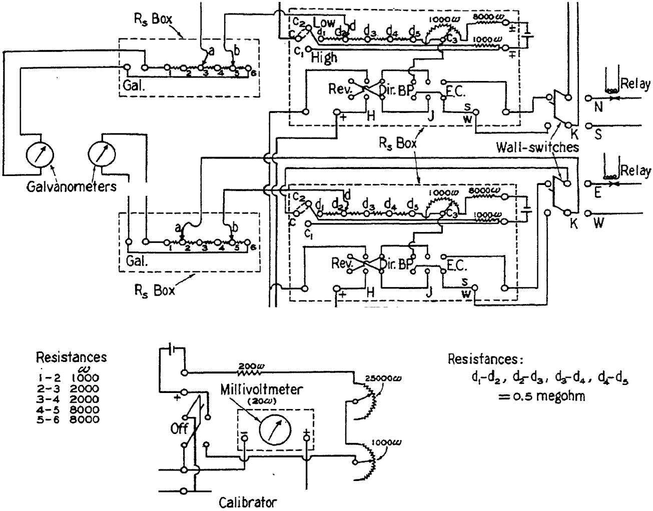


FIG. 2.—Recording circuits as used at College-Fairbanks, Alaska, 1932–33.

(*c*) Direct calibration by substituting known electromotive forces across the galvanometer-unit in place of the earth-current lines is possible and easily accomplished.

(*d*) The scale-value is constant and the reduction of the observed deflections to units of potential or potential-gradient is simplified.

(*e*) The sensitivity of the set-up can be varied over a fairly wide range without delay or much effort, thus insuring an adequate and at the same time uninterrupted record.

Neither the magnitude nor the sign of the actual potential on an earth-current line can be predicted since the contact-potentials which largely determine the recorded value may vary all the way from 0 to 0.5 volt in either direction. The contact-potentials are of course quite independent of the length of line. Since this portion of the recorded potential has no meaning from the earth-current standpoint, it is ignored in the final reduction of the data. And since, provided the electrodes are properly installed, it will either be constant or vary very slowly, it can be balanced out by applying opposing electromotive forces as shown in Figure 2, so that the mean deflections will be little or nothing. Consequently the sensitivity of the recording galvanometer can be selected without reference to the mean values recorded.

The important factors in fixing on the sensitivity to be used are the maximum deflections which occur during disturbances and the average, or better, the minimum amplitude of diurnal variation in the recorded potentials. The sensitivity must be high enough so that the latter will produce accurately measurable deflections and should be low enough so that disturbances will not cause off-scale deflections and consequent loss of record. The mean amplitude of the diurnal variation in potential-gradient varies greatly with geographical position and with the conductivity of the region. Values less than one mv per km (at Watheroo) and over 40 mv per km (at Ebro) have been recorded. Except during storms of unusual violence the disturbance-deflections at low-latitude stations are seldom greater than 30 to 50 times the amplitude of diurnal variation but at polar stations they may be as much as 200 times as great. When the ratio between the two becomes as great as this, the sensitivity chosen will generally have to be a compromise between that which will give the desirable deflection for diurnal-variation measurement and that which will give a complete record of disturbances, or it will be necessary to sacrifice one feature of the results for the other. Consequently some preliminary tests to fix on the sensitivity at a given station are required. However, galvanometers with current-sensitivity between 10^{-9} and 10^{-10} amp per mm scale-deflection will generally prove quite satisfactory. Over the range of potentials recorded on lines already established, such galvanometers can be used in series with resistances between 0.5 and 2.0 megohms, and since the set-up shown in Figure 2 can be varied in sensitivity by a factor of 200 or more without difficulty, a closer selection is hardly ever necessary.

One other point might be mentioned in connection with the selection of a galvanometer. There is naturally an upper limit to the resistance which can be profitably used in series with it. This limit is reached when the series-resistance becomes comparable with the insulation-resistance of the system, under which condition an appreciable part of the current will leak back into the ground instead of passing through the galvanometer-unit.

Galvanometers for earth-current work should be as stable mechanically as possible and have low temperature-coefficients, particularly when used in temporary installations where solid instrument-piers and close temperature-control are not available. Since most of the important variations in earth-currents are of relatively long period, the period of the galvanometers is not important except in special cases. Galvanometers satisfactory in other respects are apt to have a period quite suitable for the purpose.

(4) Lines

Well-insulated underground lines are unquestionably the best for connection between the recording instruments and the electrodes. With overhead lines there is always the possibility of induction-effects due to changes in the magnetic field in the loop formed by the lines and the ground or of electrostatic charges on the lines. Under normal meteorological conditions neither of these is of importance as has been shown by direct comparison of simultaneous records obtained with the two types of line-construction at Watheroo. The same comparison, however, shows that the underground lines have a tremendous advantage during thunder-storms. No effect at all was observable on the underground lines during such storms while large and typical disturbances were found in the records obtained with overhead lines—so large in fact that the records secured with the latter are quite worthless while thunder-storms are in progress. Unfortunately it is seldom practical to use underground lines, even where thunder-storms are frequent, because of the expense entailed. At Huancayo, where thunder-storms are of almost daily occurrence during part of the year, considerable loss of record results from this cause and the recording mechanism is damaged from time to time by heavy surges of current during the storms, but the rocky nature of the terrain makes the cost of underground lines there prohibitive.

The insulation-requirements for an earth-current line are those of a good power- or communication-system. The insulation-resistance should never be permitted to fall below that specified for the electrode-connectors. In one respect the overhead lines generally used have an advantage over underground lines. Their insulation-resistance is more readily maintained at a high value. The main points at which leakage may be expected is at the lightning-arresters, which tend to become fouled after the passage of severe storms and must be cleaned periodically. Switches for disconnecting the lines from the recording apparatus and the electrodes should always be provided to facilitate insulation-tests and to insure that such tests will be made frequently.

In many cases the layout of the earth-current measuring system, the distances between electrodes, and the direction of the lines joining them are fixed by the fact that it is necessary or convenient to use existing wire-lines and the only optional feature of the installation is the choice of the most favorable electrode-sites near the ends of the lines. Where special lines are erected, the pairs of electrodes will usually be placed on due south-north and west-east lines, respectively. This arrangement will be departed from only where, as at Ebro, satisfactory electrode-sites are not available along geographical axes. The minimum number of electrodes required is three, used in a right-angle common-point arrangement like that at Watheroo. A better arrangement calls for four electrodes so located that the lines joining the two electrodes of a pair cross approximately at their centers. This layout, used at Huancayo and at the Polar-Year stations at College-Fairbanks and Chesterfield, has the advantage over the three-point arrangement in a number of respects. The use of separate electrodes for each component eliminates the possibility of "cross-action" by which the potentials on one line may affect the record obtained on the other and also prevents undue weight being given to the characteristics of a single electrode, the common one. Further, the potentials determined on the two lines of the four-point system are those across practically the same section of the ground and the records of the two components are more strictly comparable for this reason—a factor which may be of importance should any local inhomogeneity in structure exist.

Except where it is necessary to use a given recording apparatus of fixed sensitivity there is a wide latitude in the lengths of line or distance between electrodes which can be used. Successful measurements have been made on lines less than one and more than 200 km long. There are both advantages and drawbacks in the use of either long or short lines. On long lines the potentials attributable to electrode-effects are a smaller percentage of the total recorded values since they are independent of the length of line while the earth-current potentials are proportional to it. The magnitude and constancy of this component are consequently of less importance. Somewhat lower sensitivity of the recording apparatus is required on long lines so that more rugged instruments can be used. And finally the records from long lines are less likely to be influenced by local inhomogeneities in structure. However, this last advantage is to a great extent offset by the greater likelihood of the existence of grosser inhomogeneities in the greater area covered.

Short lines, on the other hand, are cheaper to construct and easier to maintain. They can be located so that the terrain and structure included in the measurements will be fairly uniform, or, what is more important, the area included can be investigated with reference to its conductivity and homogeneity, with the result that the measurements are made with a better knowledge of the conditions affecting them.

Practically, the deciding factor in choosing the lengths of line is the expense. Long lines are used where existing lines are available for the work and short ones whenever special lines must be set up. The following are the lengths of line used at some of the more permanent stations, past and present.

Greenwich..........	Northerly	25 km	Easterly	15.6 km
Berlin..............	Northerly	120	Easterly	262
Ebro...............	Northerly	1.3	Easterly	1.4
Tucson.............	Northerly	56.8	Easterly	93.9
College-Fairbanks...	Northward	1.3	Eastward	1.2
Chesterfield.........	Northward	1.3	Eastward	0.9
Watheroo (duplicate)	Northward	3.4 and 2.0	Eastward	9.9 and 5.6
Huancayo (duplicate)	Northward	2.9 and 1.8	Eastward	2.4 and 2.0

The liability of earth-current measurements to error because of electrochemical changes at the electrodes or of inadequacies of the insulation of the system has been pointed out as has the fact that errors from either source are not readily detected. So it often happens that the gradual modifications of the recorded potentials produced by such errors are unnoticed or misinterpreted as indicating a real change in earth-current flow. For this reason independent check-measurements are of unusual value, since no tests made on a single line can be quite conclusive. Hence it was that the installations at Watheroo and Huancayo were made with multiple lines and electrodes, and two or more records of each component are secured there continuously. The duplicate installations have proved of great service in detecting poor electrode-performance, in maintaining satisfactory recording, and in establishing the validity of the records [885]. Even when there is no question as to the proper functioning of the apparatus, the duplicate records may be useful in confirming or explaining unusual features of the records such, for instance, as those due to structural peculiarities of the region.

When galvanometers are used, duplicate instruments as well as lines and electrodes are required if simultaneous, independent records are to be obtained. The added expense will be justified by the greater certainty of the records. Duplicate lines are practically never possible if the distance between electrodes is very great. So the desirability of check-measurements is an argument in favor of short lines. Where complete duplication is not possible, some of its advantages can be secured by installing additional electrodes to be used in alternation with the regular ones; and even where this cannot be done, some check on the performance of the system can be obtained by recording with different combinations of electrodes from time to time. In this way the influence of any extraneous effects associated with a given electrode will be shifted in varying degree from the records of one component to those of the other and, since such effects are independent of the lengths or directions of the lines, their importance can be determined from a comparison of the several sets of records. The four-point cross-arrangement of electrodes affords better opportunity for checks of this kind.

(5) Resistivity

A knowledge of the conductivity or resistivity of the ground is required to round out the determination of earth-current flow. Measurements in the laboratory of the resistance of the constituents of the Earth are abundant but such results are not of much value for the purpose since the resistivity of rocks and soil depends largely on their physical environment, particularly on the amount and character of the solutions they contain. Consequently the measurements must be made with the materials in place. The resistivity, except near the surface, unlike the potential-gradient, is not subject to wide variations with time; hence the determination in a given case can be made once for all, due consideration being given to the possibility of slow changes which may accompany seasonal variations in rainfall and temperature.

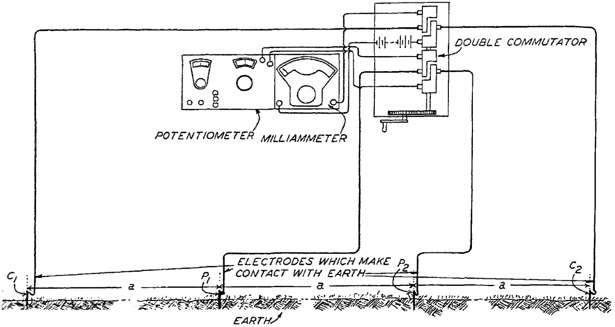


Fig. 3.—Diagram of earth-resistivity meter and connections to earth.

A method and apparatus for the determination of the resistivity of undisturbed earth, based on the laws of the four-terminal conductor as determined by Searle and Wenner, was developed by Gish [875] and has been used in surveys in the regions about the earth-potential measuring systems at Watheroo, Huancayo, Ebro, and Tucson [890, 891]. The scheme is shown diagrammatically in Figure 3. With four electrodes set in the ground at equal intervals along a straight line, a measured current is sent between the outer pair and the resulting potential-difference between the inner pair is observed at the same time. On the assumption of a homogeneous conductor, the resistivity is given by the formula

$$\rho = 2\pi aV/I$$

where a is the distance between adjacent electrodes. When, as is the case with earth-materials, the conducting body is not homogeneous, the value of resistivity so determined is a general average in which the material near the line of electrodes has the most influence and material at a greater distance from this line than the interval between electrodes has little effect on the result. So the body of earth included in a given determination has linear dimensions of the same order as the electrode-spacing and greater depths of earth may be included by increasing the spacing. In this way the variation of resistivity with depth can be determined. A number of series of measurements made with successively increased spacing, suitably distributed over a region, gives the vertical and lateral distribution of the resistivity-values.

In order to minimize the effects of polarization at the electrodes and to eliminate contact-potentials and those due to other currents present in the ground, a double commutator is inserted in the lines between the meters and electrodes. One section of the commutator reverses the current periodically and the other rectifies the resulting potential-differences so that they can be measured with the direct-current potentiometer, while all the extraneous potentials are balanced out by the reversals. With a well-constructed commutator so adjusted that the potential-circuit is never closed while the current is varying at make or break and with a guard-ring arrangement which prevents leakage between the two circuits, measurements of high accuracy are possible. Determinations of resistivity at electrode-separations from one to 600 meters have been made with a probable error certainly less than one per cent over a wide range of resistivity-values.

In addition to providing data on the general resistivity of the regions where earth-potential measurements are in progress and on its relation to the geological structure, the resistivity-surveys also show that the seasonal change in resistivity is a negligible factor in determining earth-current flow. Such changes as occur are confined to a shallow surface-layer and even at Watheroo where, during the sharply defined wet season, the resistivity of the porous sandy surface-soil changes by a factor of 20 or more, the average resistivity to a depth of 100 meters is not appreciably affected. The resistivity-survey at Huancayo was also of service in fixing the cause for some discrepancies in the early duplicate records there, due to structural differences in the area covered in the measurements.

The resistivity of earth-materials varies over such a wide range and depends to such an extent on moisture-content that average values are not particularly significant. Values as low as 90 ohm-cm and as high as 5×10^6 ohm-cm have been recorded. The following give a general idea of the ranges for some of the constituents commonly encountered.

	Ohm-cm
Clays, dense alluvia, etc.	100 to 3,000
Sedimentary rocks, new	1,000 to 30,000
Sedimentary rocks, old	30,000 to 200,000
Igneous rocks	50,000 to 500,000
Coarse gravel, sand, etc.	75,000 to 5,000,000

(6) RESISTIVITY-MEASUREMENTS IN GEOPHYSICAL PROSPECTING

An important outgrowth of the development of the method for precise measurement of earth-resistivity has been the application of such measurements to the detection and location of concealed structural features. Starting with the experiments of Gish and Rooney [875, 932], in 1924, the resistivity-method of prospecting has been used by a number of investigators with considerable success in the determination of such features as the depth of overburden and the distribution of materials in it, the depth to water-table, the contour and character of the underlying rock, and the location of mineralized areas. Description of these investigations, which are based on a study of the variations in recorded resistivity with the position and spacing of the electrodes, cannot be given here. References to them can be found in "Geophysical Abstracts" published by the United States Bureau of Mines, and detailed accounts of much of the work appear in the volumes of the "Transactions" of the American Institute of Mining and Metallurgical Engineers entitled "Geophysical prospecting."

The basis for interpreting the resistivity-data in terms of structure is found in the fact that the linear dimensions of the volume of earth included in a given determination are approximately equal to the distance between adjacent electrodes. That this is not strictly true, particularly in an inhomogeneous body, is evident from a consideration of the distribution of current and potential in a conductor under the prescribed conditions. As the resistivity-method of prospecting came more into use, a great deal of work was done in the way of working out the exact mathematical relation between variations in recorded resistivity and changes in structure [908, 930, 936, 1395, 1405, 1409, 1412, 1413, 1414, 1418, 1421, 1422, 1424]. Even for the simpler cases of two or three horizontal homogeneous layers, the calculations involved are tedious. For more complicated arrangements an exact solution is sometimes impossible but by successive approximations the general relationship can be determined. The results of these investigations, combined with experiments in the field and laboratory to confirm them, have advanced the method until it has become a tool of recognized value to the geologist and engineer.

It must be borne in mind that exact and univocal interpretation of the data from resistivity-measurements, taken alone, in terms of structure is possible only in rare instances. Fortunately the necessity for an absolute method is also rare. Indications at the surface and a general knowledge of the geological conditions of the region will usually eliminate many of the combinations of variables which can produce a given effect and so will enormously simplify the work of interpretation.

One important feature distinguishes the resistivity-method from any other of the physical methods of exploration. Where it can be used at all, the resistivity-method gives indication not only of the presence of a structural inhomogeneity but also of its depth or distance from the line of measurement. In most methods, the effect of a large mass at a distance cannot be distinguished from that of a small one near-by. With the resistivity-method, distance affects only the sensitivity of detection and that in a strictly proportional manner. Hence in measurements over a poorly conducting region, the indications from a given conductor at a depth of 1,000 meters would be just as definite as those from one with mass one-hundredth as great located at a depth of ten meters, provided the regions were equally homogeneous in both cases. There would, however, be no possibility of confusing the indications from the two. In this respect the resistivity-method is unique.

IV. RESULTS OF OBSERVATIONS

(1) Constant or unidirectional currents

The fact that almost all if not all of the mean values recorded on earthed lines must be attributed to electrochemical effects at the electrodes has been recognized by most investigators from Weinstein to the present day. The most direct evidence that this is the case is found in the multiple records obtained at Watheroo and Huancayo [885]. When these simultaneous, independent records are compared, it is apparent that the absolute or mean potentials recorded have no relation to the length or orientation of the line, are not affected by earth-current or magnetic storms, and exhibit, in general, no characteristics which indicate that they have any significance as far as earth-current flow is concerned. The conclusion to be reached from this comparison and from an examination of the records at other stations, such for instance as the results when using the "water"-electrodes at Ebro, is that there is no evidence of the existence of a "constant part" or unchanging component in earth-currents. In other words earth-currents must be considered as alternating currents, although of relatively long periods of alternation. This point can hardly be over-emphasized at the start of a discussion of earth-current results, because (1) it means that our knowledge of the phenomenon must be derived solely from a study of the shorter-period changes in the recorded potentials and (2) it is so frequently overlooked. Tables or charts showing mean values recorded from day to day, or the seasonal or other long-period changes in them, are absolutely meaningless as far as the current flowing through the ground is concerned. Yet such data have been made the basis for considerable discussion of earth-currents and this has in some instances led to serious misapprehension as to their fundamental characteristics. For the present at least only the variations are important and the discussion must be restricted to them. This restriction is a distinct handicap, it is true, but the failure to realize its existence has been an even greater one.

The present discussion will also be limited to horizontal currents or current flowing parallel to the surface of the Earth. Vertical earth-currents are reported by some observers [870, 879, 883, 1391, 1392, 1393, 1396], but all the evidence adduced to show their existence is of the nature just referred to as irrelevant. Until some method of measurement free from the effect of contact-potentials can be developed, or some other carefully controlled experiments demonstrate conclusively that there is any vertical flow other than that which may occur when a generally horizontal flow is diverted to a higher or lower stratum because of non-uniform conductivity, they must remain a subject for speculation only.

(2) DISTURBANCES, EARTH-CURRENT STORMS

The variations first encountered, those most readily apparent in the records of potential, are irregular fluctuations, sometimes of brief duration and sometimes continuing for several days. These disturbances or earth-current storms have been examined in comparison with similar disturbances in the magnetic records and the two are found to be very closely related, particularly as to time of occurrence. The statement is sometimes made that magnetic disturbances are always accompanied by earth-current disturbances, but that, in certain instances, disturbances in earth-currents occur when the magnetic conditions are undisturbed. The records with which the writer is familiar do not bear out the accuracy of this statement. It is conceded that disturbances in the *records of potential* may and do occur when the magnetic conditions are quiet, but it does not follow that every disturbance in the records indicates abnormal earth-current flow. Violent and characteristic disturbances will usually be found in the records obtained on overhead lines during thunder-storms, and less-pronounced irregular fluctuations can often be traced to sudden changes in the mechanical or chemical conditions at one or more of the electrodes or to leakage from commercial power-systems. It is quite probable that disturbances in the records from such sources have been attributed to unusual earth-current activity, particularly when only a single record of the potentials was available. One of the chief advantages of the multiple recording systems at Watheroo and Huancayo is the opportunity they afford to check on features like these. If any appreciable disturbance which could not be attributed to one of the causes just enumerated has occurred at these two stations without a simultaneous disturbance in the magnetic records, it has escaped attention.

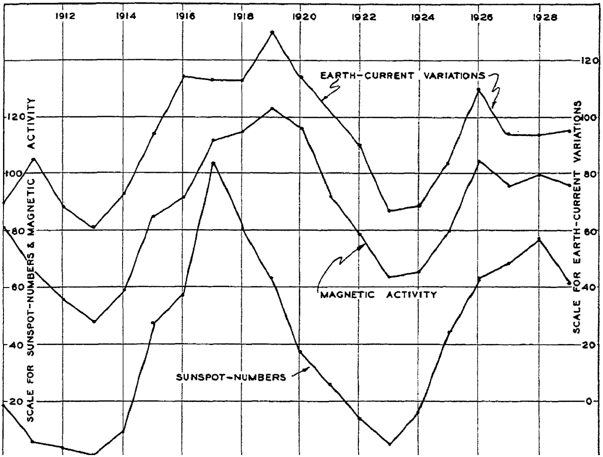


FIG. 4.—Comparison of changes in earth-currents, magnetic activity, and sunspot-numbers.

Earth-current storms vary widely in type and intensity just as do magnetic storms. Potential-gradients of several volts per km have been observed in extreme cases. World-wide storms, often characterized by abrupt commencements which occur at the same time at widely separated stations, are noted and coincide with similar magnetic storms. More local disturbances are also found to occur, the latter being particularly pronounced at high latitudes. The correlation between earth-current and magnetic disturbances is shown in a general way in Figure 4 by the variations in the activity of each through the sunspot-cycle. The 27-day recurrence in disturbances has also been shown by Peters and Ennis [884] to be a feature of the earth-current as well as of the magnetic records.

Although an exact relationship is not apparent, the connection between earth-current and magnetic disturbances is not merely one of coincidence in time. Examination of a large number of records shows a fairly constant agreement in the nature of the disturbances in the two, like fluctuations appearing in the earth-current records when the same type of disturbance is found in the magnetic records. At Watheroo and Ebro, both middle-latitude stations, the successive deflections in the earth-current records follow closely those in the traces of magnetic vertical intensity and declination, while at Huancayo, near the equator, the agreement is closest between changes in earth-currents and those in magnetic horizontal intensity. A noteworthy feature of earth-current disturbances

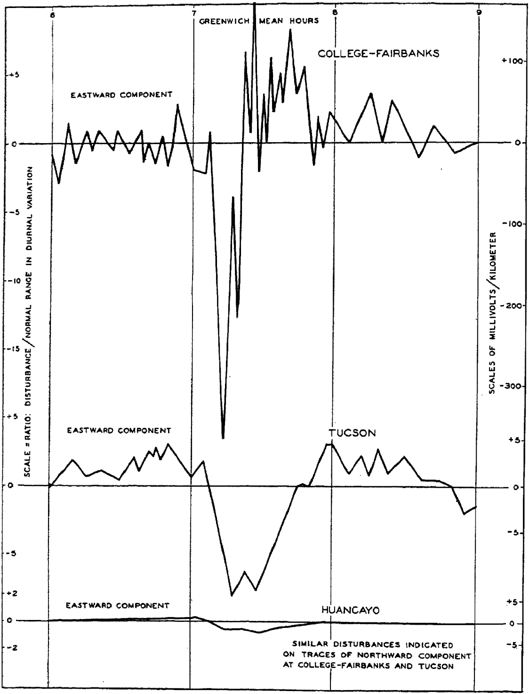


FIG. 5.—Short-period earth-current disturbance accompanying isolated auroral display at College Fairbanks, Alaska, with simultaneous disturbances at Tucson and Huancayo, December 31, 1932.

is that the ratio of the magnitudes of the deflections recorded for the two rectangular components remains fairly constant most of the time, showing that the direction of current-flow is generally restricted to surges back and forth along a more or less fixed line. At middle-latitude stations this line is more nearly along a south-north than an east-west direction and often corresponds closely to the magnetic meridian.

Another point of similarity in the earth-current and magnetic records is that the frequency and intensity of disturbances, particularly disturbances of short duration, are greatest at high latitudes. At low latitudes, except under extreme storm-conditions, the deflections due to disturbances are rarely more than 20 to 30 times the amplitude of the regular periodic variations which occur during the day, while at College-Fairbanks and Chesterfield short-period deflections 100 to 150 times as great as the normal daily range are of frequent occurrence. It should be noted, however, that, in some cases at least, these large, brief polar disturbances are not strictly local but rather indicate a local intensification of a wide-spread electrical effect, since the same disturbances, greatly reduced in magnitude and modified in appearance, can be detected in the records at lower latitudes. A typical case is shown in Figure 5. A brilliant auroral display was observed at College-Fairbanks [887] at the same time as the disturbance here shown, and there has been found a high degree of correlation, both general and particular, between earth-current and magnetic disturbances and the auroras at the few polar stations for which earth-current data are available. But because of the fact that, as shown in Figure 5, disturbances at a given station may be associated with distant auroras as well as with those visible at that station, the whole story as to the relation between the two cannot be obtained from the records at a single station. A really searching investigation of the relationship could be carried on only by securing simultaneous records of the two at a number of stations near the auroral zone.

(3) PERIODIC CHANGES

Studies based on disturbances are handicapped by the irregularity and diversity of their effects and by the difficulty of fixing on simple quantitative measures for the complex fluctuations. For this reason the more regular periodic variations offer a field of investigation more favorable in many respects.

The variation most readily susceptible to analysis and to statistical treatment in general is the regular diurnal variation. Curves and tables giving the average departures of the mean potential-gradient during each hour from the mean of day are available from the records at a dozen or more stations. Until recently the distribution of the data has been rather unsatisfactory, most of the stations being close together in Europe.

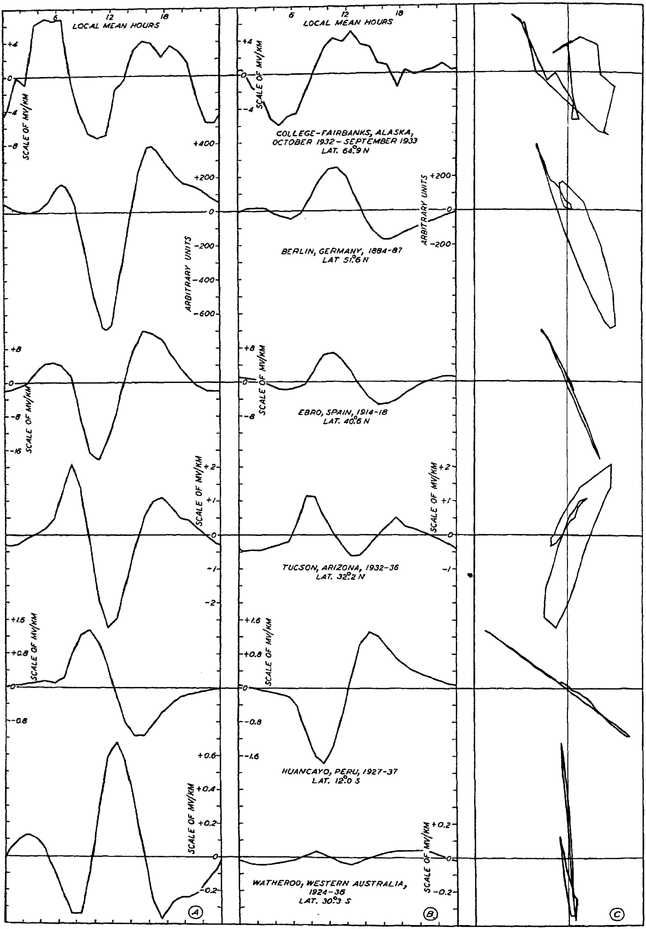


FIG. 6.—Diurnal variation in earth-current potential-gradient for different latitudes; A = northward component, B = eastward component, C = hodograms.

Diurnal-variation curves for six stations fairly well distributed in latitude from 64° 54′ north to 30° 19′ south are shown in Figure 6. Five of the six pairs of curves are based on three years or more of observation. The curves for College-Fairbanks are the means for a single year only but are included because of the scarcity of observations at high latitudes. The essential features of the variations at this station have been confirmed by records obtained simultaneously at Chesterfield [866] in latitude 63° 30′ north; hence they may be regarded as typical.

When the diurnal variation is given in terms of potential-gradient, the amplitudes of the curves for the several stations differ greatly. Hence the same scale of ordinates could not be used in constructing the curves in Figure 6 and they are comparable only as to form and not as to magnitude. For four of the stations—Ebro, Tucson, Huancayo, and Watheroo—data on the resistivity of the ground are available and it is possible to present a somewhat more quantitative picture of the situation in their cases. Because of the wide variations of resistivity with depth and some uncertainty as to the exact depths involved in earth-current flow, even this will be only approximate but is less likely to be misleading. Neglecting the variable surface-layer of soil and considering the material lying between 20 and 200 or 300 meters below the surface, the resistivities of the four sites are roughly in the ratios of 12, 4, 10, and 1. If then the recorded potential-gradients are divided by these respective figures, the resulting curves, as shown in Figure 7, can be taken as roughly proportional to the current-densities.

At middle-latitude stations, as will be seen in Figures 6 and 7, the northward component is decidedly predominant and the diurnal-variation curves are definitely of double period with a marked maximum flow of current toward the equator occurring close to midday. At Watheroo and Tucson, which are at approximately equal distances on either side of the equator, the maximum flow from it (southward at Watheroo and northward at Tucson) occurs during the forenoon, while at Ebro and Berlin, both farther north, the afternoon maximum is somewhat the greater. At all four stations, as will be seen in the hodographs on the right in Figure 6, the direction of current-flow is restricted rather closely to a direction which is not far from the magnetic meridian at each place. This restriction in direction of flow is found often in earth-current records. It is sometimes attributed to the effects of local geological structure in distorting the lines of current-flow but appears to be too general a characteristic to be explained entirely in this way. Moreover at Tucson the hodograph is greatly elongated along the magnetic meridian during the summer and rather symmetrically rounded during the winter [888], the change being quite definitely not related to resistivity-changes; restricted hodographs are also obtained at stations where the structure, as far as we know it, is puite uniform.

The diurnal variation at Huancayo in latitude 12° 03′ south is of a distinctly different type with a single pronounced maximum and minimum which occur roughly at the times when the variations at the middle-latitude stations are zero. So the Huancayo curves are very like the integrations of the Watheroo or Tucson curves or the latter resemble the derivatives of the Huancayo curves. The direction of current-flow at Huancayo, again decidedly restricted, is much more nearly at right-angles to the magnetic meridian than along it. In this respect the records tend toward agreement with theoretical predictions that the eastward component should predominate at low latitudes.

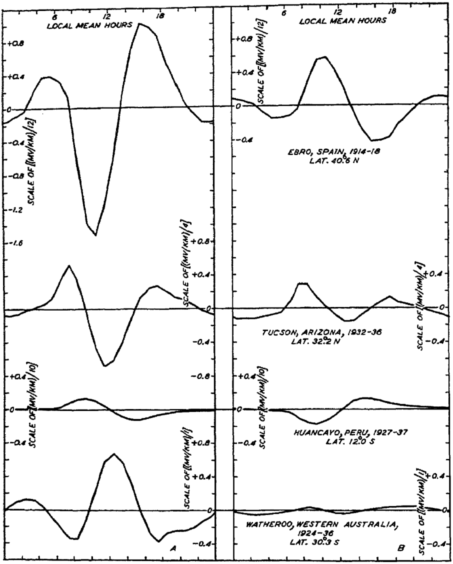


FIG. 7.—Diurnal variation in earth-currents for different latitudes, to same scale of current-density on basis of results of resistivity-surveys; *A* = northward component, *B* = eastward component.

While too great weight must not be given to the single year's records from College-Fairbanks, the curves for that station suggest that the type of diurnal variation again changes as high latitudes are reached with the eastward component once more becoming relatively more important. The hodographs for this station do not indicate a close restriction in the direction of flow but the records, particularly during disturbances, do show a tendency toward flow along a line 20° to 30° west of north. Since the declination at College is a little over 30° east, the preferred direction of flow is again, as at Huancayo, more nearly at right-angles to the magnetic meridian than along it. Unfortunately no resistivity-records were secured at College; hence the relative amplitude of the variation there to that at the middle-latitude stations can be estimated only in terms of current-density. In view of the permanently frozen subsoil there, the resistivity of the region is probably much higher than at the other stations. Hence could the data be presented on the same basis and to the same scale as those in Figure 7, the curves for the polar station might be expected to have a smaller amplitude than any of those shown.

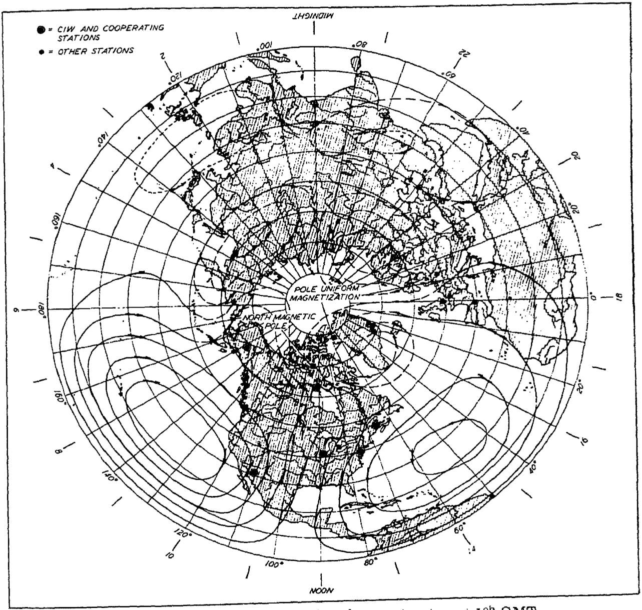


FIG. 8.—Polar view of position of earth-current system at 18^h GMT.

With the data now available from polar and equatorial stations and the more widely distributed records recently obtained in the middle latitudes, it is becoming possible to map out in a general way the circulation represented by and responsible for these diurnal-variation records, without too much recourse to speculation or to arbitrary assumptions. By far the most comprehensive picture presented to date is that given recently by Gish [873]. This is shown in Figure 8 for the Northern Hemisphere, and in Figure 9 as viewed from a point above the equator. In constructing these figures the density of the arrows shown along the several parallels of latitude was obtained by integrating the recorded longitudinal flow throughout the day and their direction was determined directly from the diurnal-variation curves. The lines joining each pair of arrows were then drawn in so as to complete a circulation consistent with the general features of the several records. So treated the data from all the stations show the existence of a system of current-whorls eight in number, rather symmetrically spaced with reference to the equator and a secondary series of similar whorls near the pole. The whorls in the daylight side of the Earth are large and well defined, while those on the dark side are far less definite.

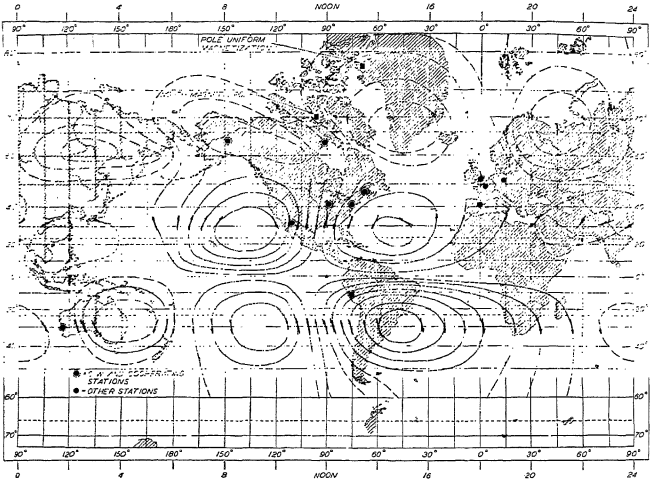


FIG. 9.—Equatorial view of position of earth-current system at 18^h GMT.

These current-whorls should be considered as fixed in space directly under the Sun with any point on the Earth occupying successive positions in them as it rotates on its axis. At the instant depicted it is 18^h Greenwich time, about 11^h local time at Tucson, 13^h at Huancayo, and shortly after midnight at Watheroo. Upon examination of what happens as a point on the map moves from left to right across the whorls, the significance is readily apparent of such commonly noted features of diurnal variation at middle-latitude stations as the generally longitudinal direction of current-flow, the large surge of current toward the equator near noon, and the reversals of direction occurring during the forenoon and afternoon. The diagrams also show why the usual direction of current-flow at stations near the equator is nearly at right-angles to that recorded at higher-latitude stations.

In constructing the diagrams the resistivity of the Earth and the non-uniformity of the Earth's magnetic field were neglected. Hence the circulation shown is more or less qualitative and approximate. It is also necessarily generalized because of the fact that only a comparatively small portion of the Earth is covered by existing stations and the polar records, in particular, are limited in time as well as distribution. It should be borne in mind that an exact picture could not be presented in a single diagram in any event, since it is obvious that, even if the inducing forces remained constant, certain modifications in the current-whorls must take place as the character of the region each occupies changes. The resistance of the current-paths, for instance, must be very different for a deep oceanic region and for a continental area. Consequently exact duplication of diurnal variation at two stations at the same latitude, as indicated by Figures 8 and 9, is not obtained and cannot be expected.

The seasonal changes in earth-current activity, as evidenced by the diurnal-variation curves for the individual months, are chiefly changes in intensity. This holds particularly for the northward component, and since the relationship between the two components is quite constant at all but one or two stations, it is usually true of the eastward component as well. In Figure 10 the range in the mean hourly values recorded at six stations is charted for each month of the year to show how the seasonal change progresses. All the curves are quite similar with the exception of that for Tucson. The seasonal change at that station will be discussed separately. The others show a decided minimum of activity at midwinter and maxima near the equinoxes, that occurring in the spring being usually the greater. Sufficient data were not secured at College-Fairbanks to permit reliable figures to be assigned to the ranges in individual months there, particularly in view of the frequent large disturbances in these polar records. The range was, however, found to be markedly smaller during the winter than in the summer and to that extent the records are in agreement with those from the lower-latitude stations.

At Huancayo the change in intensity is the only seasonal change apparent in the records. There is practically no shift in the times of day at which the current-flow is maximum or minimum and the phase-relationship between the two components remains the same throughout the year.

At all the middle-latitude stations except Tucson the relative magnitudes of the two components remain about the same throughout the year and there is no marked difference in their phase-relationship. However there is some shift in the times at which the principal maxima and minima occur. The maximum flow in morning away from the equator and the noonday peak of flow toward it are reached earlier in the summer than in the winter. The afternoon maximum of flow away from the equator occurs more nearly at the same time throughout the year. As a result of the constancy of relationship between the two components the only changes noted in the hodographs, when constructed for individual months,

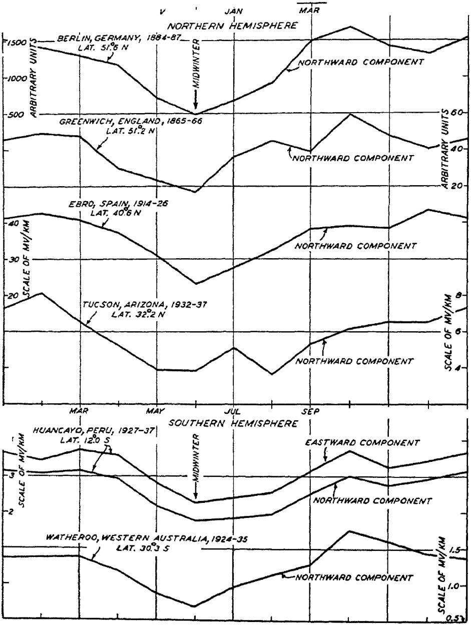


FIG. 10.—Seasonal changes in range of diurnal variation for the principal component of earth-current potential-gradient at six stations.

are an expansion and contraction of the daylight portions of the graphs, the characteristic shapes persisting as shown in Figure 6.

Records from the recently established station at Tucson show a striking departure from the usual seasonal variation at middle-latitude stations. Tucson is uniquely located, lying in the so-called transition-belt where the diurnal variations in magnetic dip and intensity change from higher-latitude to equatorial type and the curves for these elements are markedly different at different times of the year. For this reason the

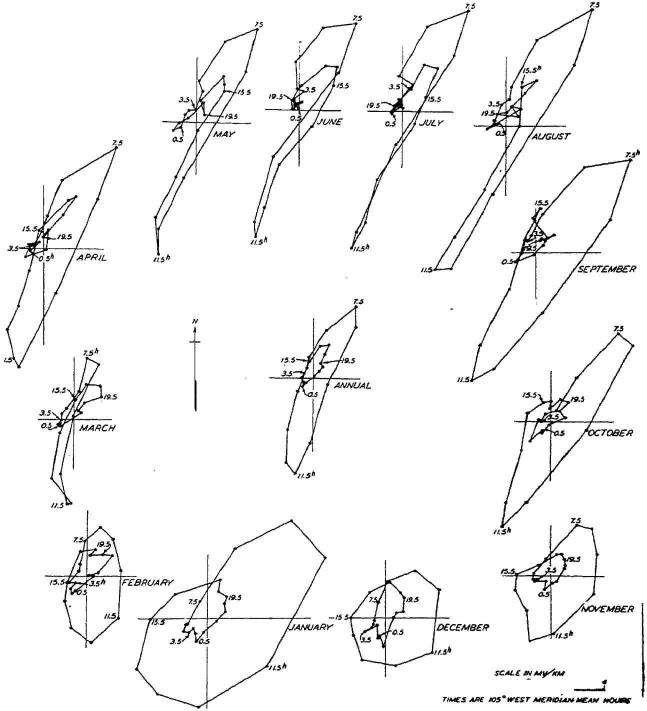


FIG. 11.—Seasonal change in earth-current diurnal variation at Tucson, Arizona, ten calm days per month for three-year period, 1932–34.

earth-current curve at this station is of particular interest. If the northward component alone were considered, the seasonal variation at Tucson would be found nearly normal except for a sharp increase in range during January. Aside from this the seasonal change is quite like that noted in the northward components at Watheroo, Ebro, Berlin, and Greenwich, consisting of a large increase in amplitude and a small forward shift in the times of maximum flow with increasing height of Sun and a corresponding diminution and retardation during the winter. The changes in the diurnal variation of the eastward component, on the other hand, instead of following closely those in the northward component, as they do at the other stations, are distinctly different. The amplitude or change in range in this component is small and somewhat irregular, the maximum range occurring in January and the minimum in March. The main feature of the seasonal change in this component is a large shift in phase which amounts almost to a reversal in direction from winter to summer.

Both components being taken together, the seasonal variations at Tucson are best shown by the series of monthly hodographs in Figure 11. The sharply marked changes in the appearance of the graphs from month to month have been repeated very closely in each of the six years that the station has been in operation, even to the details of the diversely anomalous graphs for January and March. That these changes are significant cannot be doubted as will be evident later on when the records are compared with those of the magnetic field at this same station.

In addition to the seasonal changes the normal activity in earth-currents has been found to vary from year to year. Weinstein, from the Berlin records, and Stenquist and Bauer, using the data from Ebro [857, 896, 1399], show that the normal ranges as well as the disturbances follow the variations in solar activity. The records so far obtained at Watheroo and Huancayo confirm this by a high degree of correlation between the range of diurnal variation and sunspot-number. With the completion of a full sunspot-cycle of recording at these stations further data on this point will soon be available.

V. RELATION OF EARTH-CURRENT AND MAGNETIC VARIATIONS

That there is a physical connection between earth-currents and the Earth's magnetic field can scarcely be doubted. The exact nature of the relationship has, however, yet to be determined. The similarity of the fluctuations in the two during magnetic storms suggested to early observers, who had access mainly to records of disturbances, that the earth-currents might be the cause of the magnetic variations. This relationship is not borne out by comparison of the diurnal variations. Moreover Schuster [327, 1398] has shown that two-thirds of the diurnally varying magnetic field is of external origin and hence could not be due to currents flowing in the Earth.

At middle-latitude stations, comparison of the diurnal variation in the predominant northward component, N, of earth-currents with that in the eastward component, Y, of the horizontal magnetic field, shows that the variations in N do not agree with those in Y but do follow much more closely the time-variations in the Y-curve, much as if the earth-current flow were the effect of the magnetic variations. This is shown for Watheroo in Figure 12, and a similar relation is apparent in the records from Ebro, Berlin, and Tucson. There are, however, some systematic differences in phase between the curves of N and ΔY which preclude a simple cause-and-effect relationship. Where the eastward component of earth-currents is pronounced enough to be significant, its diurnal variation does not follow closely the time-variations in the curve of the northward magnetic component, X, but is rather like the X-curve itself reversed. It is apparent from such considerations that the relationship between the two is somewhat complex. Even though the earth-currents were directly produced by magnetic changes, it is evident that they should have a reaction which would affect the measured variations of the magnetic force

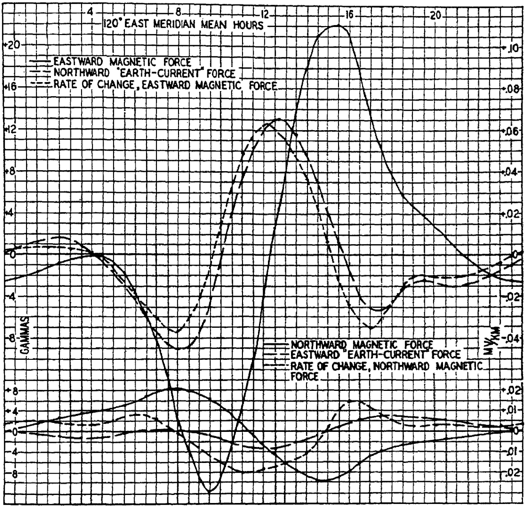


FIG. 12.—Comparison of earth-current and magnetic variations at Watheroo, 1924–26.

and the strength of this reaction would depend on the internal structure of the Earth, concerning which comparatively little is known with certainty. Hence too simple a relationship cannot be expected.

The comparisons exemplified in Figure 12 are based on mean values over long periods of time. That the similarities noted in the two sets of records are not merely fortuitous but indicate a real relationship between the two phenomena is evidenced by a consistent parallelism in the changes undergone by each. Records of diurnal variation on calm and disturbed days from Watheroo, Ebro, Huancayo, and Tucson, all show that the small, but definite and distinctive, differences found in the magnetic variations during disturbed periods are also found in the earth-current records, the disturbances apparently affecting both alike. Again the seasonal changes in normal activity shown by the ranges in earth-current variations in Figure 10 are quite like the seasonal changes in the magnetic variations.

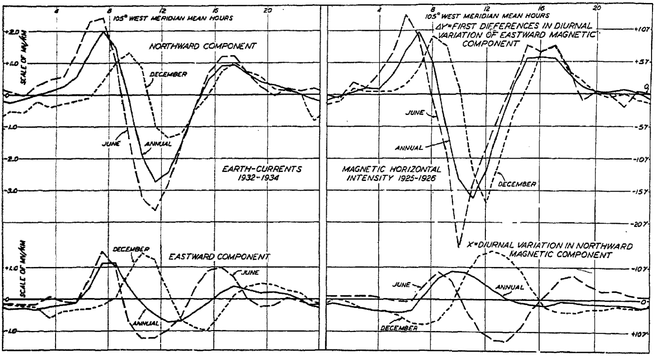


FIG. 13.—Calm-day diurnal-variation in June and December at Tucson, Arizona, showing parallel changes in earth-current potential-gradient and magnetic horizontal intensity.

The records at Tucson afford an opportunity for a closer comparison in this respect because of the unusual character of the changes shown in Figure 11. It is quite convincing to note that the seasonal variation in earth-currents there has its counterpart in the records of the magnetic elements at that station. So in Figure 13 the general qualitative correspondence between the curves of N and ΔY and of E and $-X$, respectively, will be seen to hold not only for the mean annual diurnal-variation curves but also for those recorded in the months of greatest contrast in type, namely, June and December. The parallelism in the changes in the two is found to extend also to the anomalies noted during January and March and can hardly be considered to be accidental.

An even more specific case of parallelism, involving no statistical treatment of the data at all, was noted by Bartels [1388] while investigating the variability of quiet-day diurnal variation in terrestrial magnetism at Watheroo. This is shown in Figure 14. These last two instances make it appear that a day-by-day comparison of the diurnal variations may be expected to bring out the connection more clearly.

Chapman and Whitehead [864], in their investigations of the mathematical relations between the magnetic variations and the external and internal magnetic field, developed formulas for deriving the earth-current potential-gradient from the potentials of the magnetic variations, based on estimated conductivities of the core and surface-shell of the Earth. Applying these formulas, which involve the variations in magnetic vertical intensity, to Berlin and Ebro, Chapman found a rough qualitative agreement between the predicted and observed diurnal variation, the agreement being a little better for the northward than for the eastward component. No quantitative check could be made for the results at Berlin because the earth-current records there are reported in arbitrary units. At Ebro the amplitude of the observed curves was about five times that of the computed ones. The same formula applied by the writer to the north-

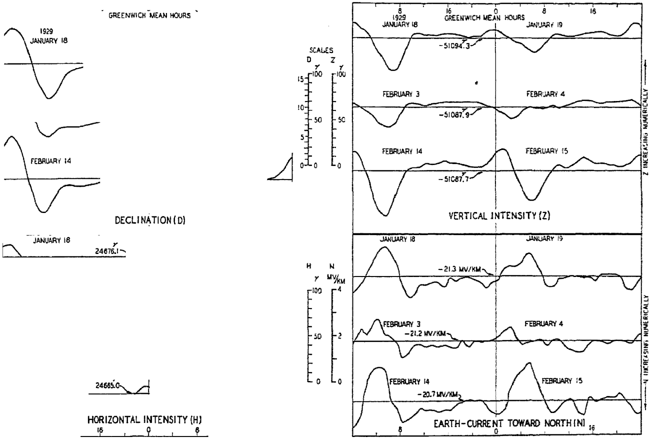


FIG. 14.—Example of parallelism in variability of quiet-day diurnal variation in earth-currents and magnetism at Watheroo.

ward earth-current component at Watheroo again resulted in diurnal-variation curves quite similar in appearance but this time the amplitude of the observed curve was only one-sixth that of the computed one. The fact that the computed curves have a smaller amplitude than the observed ones at Ebro where the resistivity is relatively high, and a greater amplitude at Watheroo, where the resistivity is unusually low, indicates that the discrepancies may be due in part at least to this factor. A ratio of 10 to 15 in the discrepancies when applying the formulas to these two sites would be right in line with the results of the resistivity-surveys made there. In view of the fact that the average resistivity of the entire paths of current-flow and that of the core of the Earth itself are involved, as well as the local resistivity at the site of measurement, the difference between the resistivity-ratio and that of the discrepancies in the two cases, a factor of 2 or 3, may not be important.

The earth-current records from equatorial and high-latitude stations are so meager that the diurnal-variation characteristics in these regions are not established sufficiently to warrant specific comparison with magnetic variations. The data from Huancayo do however indicate a tendency toward agreement with theory to the extent that the eastward component becomes relatively more important and a simpler type of diurnal-variation curve appears.

The theories underlying the variations in earth-currents and magnetism, as deduced from the observations of the variations and strengthened by recent investigations of the changes in the ionosphere, have been summarized by Gish [872] in the article already referred to. Briefly, the variations in both are now quite definitely assigned to the effects of currents circulating in the upper atmosphere as portions of it become highly conducting under the ionizing action of radiations from the Sun. The type of radiation and the exact mechanism of the processes are not certain, but it is safe to say that no satisfactory explanation of the magnetic variations can be adopted which will not at the same time suffice for earth-currents. Storm-variations call for a somewhat different set of phenomena again acting under the influence of radiations from the Sun, but apparently acting more directly to produce current-flow in the Earth which is accompanied by magnetic fluctuations. In both aspects the two investigations are interdependent. For details of these theories the works of Schuster [327, 1398], Chapman [282, 864], and Gunn [312] may be consulted.

VI. PRESENT STATUS OF EARTH-CURRENT INVESTIGATION

Although earth-currents are receiving more attention now than at any time since the close of the last century, the greatest need remains a better distribution of stations, particularly at high and low latitudes. Although the distribution of magnetic observatories is not yet regarded as ideal, or even adequate, there are at least 40 first-class stations continually recording magnetic variations. In contrast, we have at present only three well-established earth-current stations in continuous operation, two of which are in the middle latitudes, and the all-time number of first-class stations, which are or have been operated for any considerable length of time, is not more than a dozen. For a study of disturbances and their relation to the auroras and other phenomena, a group of polar stations is almost essential, and additional data in equatorial regions are needed to map out the diurnal variation and to determine its relation to that of the magnetic field. Even in middle latitudes, because of possibility of distortion of the general flow due to non-uniform conductivity or other structural differences, more widely distributed records would be useful to fix the importance of such features as the very restricted paths of flow so frequently encountered and so difficult of explanation on the theory of induction by currents in the ionosphere.

The fragmentary character of the observations has been a real handicap to the investigation of earth-currents, particularly since no single observation can be secured which is entirely free from the masking effects of extraneous potentials such as those due to electrochemical action. More widely distributed observations should do much to clear up the uncertainties and misapprehensions arising at times from this source and, when considered in connection with magnetic records and with the enlightening data now made available by the recently developed technique for investigation of the ionosphere, should lead to a far better understanding not only of earth-currents but of their allied phenomena as well.

CHAPTER VII

ON CAUSES OF THE EARTH'S MAGNETISM AND ITS CHANGES

A. G. McNish

Department of Terrestrial Magnetism, Carnegie Institution of Washington

I. INTRODUCTION

Although the directive power of the Earth's magnetism and its variations have been discussed for several centuries, progress in understanding the causes of these phenomena has been halting and difficult. Their riddles are even more numerous today than they were a century ago. None of these may be regarded as completely solved and the greatest of them all—the origin of the Earth's main magnetic field—has so far defied all attempts at solution.

In the days of Gilbert, the Earth was pictured as a sphere of lodestone. But this view is not simply compatible with numerous other geophysical facts. So also with variations in the field; the secular and ephemeral changes have become increasingly difficult to explain with acquisition of collateral knowledge. Only the solar and lunar diurnal variations have admitted of reasonably satisfactory explanation. This condition arises because the phenomena of terrestrial magnetism originate at great depths within the Earth or at great heights in the atmosphere, concerning which facts are few and admit ambiguous interpretations.

Observations of the magnetic field at the Earth's surface extend over a century. Although insufficient to establish the causes of the phenomena, they prescribe limits for speculation. At a number of places on the Earth's surface continuous photographic records of changes in the field have been obtained for over half a century. Nearly twoscore such stations have been in operation since 1900.

During the past few years distinct advances have been made, partly through increased effort to interpret the facts of observation and partly through attempts to correlate those facts with fresh information concerning the regions in which the phenomena originate.

Thus, although the concept of a ferromagnetic Earth has been weakened by information indicative of high internal temperatures, investigations of properties of matter at great pressures suggest that deep in the Earth radical changes in the properties of its substance may occur. Examination of some of the facts of terrestrial magnetism produces concepts of the Earth's interior which are not derived in other fields of research.

Radio measurements on the Earth's upper atmosphere have demonstrated the correctness of the fundamental assumption that it is electrified, which was proposed over 50 years ago. However, quantitative measurements of the ionic density have failed to supply a clearly adequate ionic density fully to substantiate this theory. Magnetic storms are now known to be accompanied by disturbances of the electrification in the upper atmosphere although the connection between these two phenomena is not understood. A closer connection between terrestrial magnetism and solar phenomena than recognized hitherto has been revealed by careful correlation of radio, magnetic, and solar conditions.

Proper appreciation of the problems of terrestrial magnetism requires a comprehensive understanding of the established facts and of the methods and suggestions which have been employed for their solution. The present state of knowledge has been built on these.

In this Chapter many of the observational facts will be discussed as well as the theories which have been proposed to explain them. Among such interpretative methods the process of potential analysis is outstanding. The Earth's field is admirably adapted to application of this method, which has proved to be one of the most powerful mathematical procedures used to study it.

II. HARMONIC FUNCTIONS

The potential in any given region which does not contain attracting matter must satisfy Laplace's equation

$$\partial^2W/\partial x^2 + \partial^2W/\partial y^2 + \partial^2W/\partial z^2 = 0 \qquad (1)$$

Any function which satisfies this equation is known as a harmonic function. The terms of the well-known Fourier series satisfy Laplace's equation in two dimensions.

A representation of the Earth's magnetic field is necessarily a three-dimensional problem and it is convenient in this representation to use spherical coordinates. In this discussion the following designations will be used which are consistent with terrestrial magnetic practices: r, radius, distance from point of reference; a, a constant value of r—in this case, the Earth's radius; θ, polar distance, the angle between the radius to a given point and the axis; λ, the angle between the plane including the axis and a second point of reference and the plane including the axis and the given point (reckoned positive for east longitude); x, distance along a meridian toward the "north" pole, $x = 0$ at south pole; y, distance eastward along a parallel; X, Y, Z, components of magnetic intensity directed northward, eastward, and radially downward; u, cos θ; W, magnetic potential.

Laplace's equation expressed in spherical coordinates becomes

$$\partial/\partial r(r^2\partial W/\partial r) + (1/\sin\theta)(\partial/\partial\theta)(\sin\theta\partial W/\partial\theta) + 1/\sin^2\theta\partial^2 W/\partial\lambda^2 = 0 \quad (2)$$

Any solution of this equation is called a spherical harmonic of which there are several types. The general solution of the equation, involving r, is called a solid spherical harmonic. The portion of the solution involving θ and λ only is called a surface harmonic. Surface harmonics which are symmetrical about the axis are independent of λ and are called zonal surface harmonics because the regions where they have positive and negative values divide the surface of the sphere into zones. Sectorial and tesseral surface harmonics involve λ also and divide the surface of the sphere into sectors and tesserae.

Illustrating the development of the spherical harmonic concept, the case of the solid zonal harmonics which are independent of λ will be considered. The first step is to assume within certain limitations that Laplace's equation has a solution of the form, $W = (r/a)^n P$, in which P is a function of θ only. Substituting this solution in the original equation (2) leads to

$$n(n+1)P + (1/\sin\theta)(\partial/\partial\theta)(\sin\theta\ \partial P/\partial\theta) = 0 \quad (3)$$

Further, assuming that P may be expressed as a sum of powers of $\cos\theta$, equation (3) becomes

$$n(n+1)P + [\partial/\partial u][(1-u^2)\partial P/\partial u] = 0 \quad (4)$$

since $u = \cos\theta$. It is clear that if the value of P is assumed to be given by

$$P = b + b_1\cos\theta + b_2\cos^2\theta \cdot\cdot\cdot b_n\cos^n\theta \quad (5)$$

the b's must be of such relative value that the preceding equation is satisfied. In the first term of (4), P is multiplied by $n(n+1)$, and in the second term of (4) other operations are performed on P which alter the coefficients and exponents of each term of the power-series. The coefficients and exponents must be such that after the operations are performed the first and second terms are exactly equal. A different combination of coefficients and exponents is required for each value of n. The relative values of the b's for integral values of n can be found by recursion formulas. Some values of P which satisfy equation (4) for various integral values of n are:

$$P_0 = 1$$
$$P_1 = u = \cos\theta$$
$$P_2 = (\tfrac{1}{2})(3u^2 - 1) = (\tfrac{1}{2})(3\cos^2\theta - 1)$$
$$P_3 = (\tfrac{1}{2})(5u^3 - 3u) = (\tfrac{1}{2})(5\cos^3\theta - 3\cos\theta)$$
$$P_4 = (\tfrac{1}{8})(35u^4 - 30u^2 + 3) = (\tfrac{1}{8})(35\cos^4\theta - 30\cos^2\theta + 3)$$

Each of these expressions for P is called a zonal surface harmonic of degree n, n being the subscript of P. Each by itself is a solution of the required equation and therefore any additive combination of them is likewise a solution. This may be seen readily by substituting any one of them in the equation. Thus $[5 \cos^3 \theta + 4.5 \cos^2 \theta + \cos \theta - 3]$ is a solution, being equal to $[2P_3 + 3P_2 + 4P_1]$. If, however, either the numerical term or one of the cosine-coefficients in any one of the expressions for P_n is altered disproportionally with the other terms in that expression for P_n, the altered expression will not satisfy the equation and therefore it cannot represent the physical conditions which have been hypothesized. For each of these expressions for P_n there is a corresponding function of r which was assumed as a solution for Laplace's equation. Thus arises the series of solid zonal harmonics which satisfy Laplace's equation.

$$W = aE_1(r/a)P_1 + aE_2(r/a)^2P_2 + aE_3(r/a)^3P_3 \tag{6}$$

The E's are coefficients which are determined by the particular potential which it is desired to represent. The a's set before the individual terms give the E's—the dimensions of field-strength. Thus if W is a magnetic potential, it has the dimensions $M^{\frac{1}{2}}L^{\frac{1}{2}}T^{-1}$; a has the dimension L so that the E's have the dimensions $M^{\frac{1}{2}}L^{-\frac{1}{2}}T^{-1}$; the (r/a)- and P-factors are pure numbers. Similarly the series

$$W = aI_1(a/r)^2P_1 + aI_2(a/r)^3P_2 + aI_3(a/r)^4P_3 \tag{7}$$

may be shown to be a solution of Laplace's equation.

An analysis of the Earth's magnetic field involves the determination of these parameters, the E's and the I's, for the Earth's field.

(1) APPLICATION OF HARMONIC ANALYSIS TO EARTH'S MAGNETIC FIELD

A direct determination of the Earth's magnetic potential is not possible. Measurements of the Earth's field define the components of the magnetic force, namely, the derivatives of the magnetic potential with respect to the coordinates of the points at which the measurements are made. From the horizontal intensity, declination, and inclination may be derived the three components of intensity previously defined, X, Y, and Z. In terms of the derivatives of the potential they are

$$\begin{aligned} X &= -\partial W/dx \qquad (1/a)\partial W/\partial\theta \\ Y &= -\partial W/\partial y \qquad -(1/a \sin\theta)\partial W/\partial\lambda \\ Z &= \partial W/\partial r \end{aligned}$$

If values of X and Y at various points on the Earth are known, it is possible to evaluate the derivatives of the various harmonics for those self-same points and select, by least squares or some other process, those coefficients for the harmonics which most accurately represent the observed values.

Knowledge of the vertical component is not necessary for this determination. The Earth's magnetic potential is uniquely determined by the horizontal components of the force alone. However, if the vertical force also is known at these points, an interesting and important calculation can be performed.

(2) RESOLUTION OF INTERNAL, EXTERNAL, AND NON-POTENTIAL FIELDS

Sums of a zonal harmonic series of the form

$$W = a\Sigma E_n(r/a)^n P_n$$

or

$$W = a\Sigma I_n(a/r)^{n+1} P_n$$

are known to be solutions of Laplace's equation. These two expressions for W are solutions only when the ratios, (a/r) and (r/a), are equal to or less than unity—in other words, the first expression satisfies Laplace's equation within the sphere, $r = a$, while the second satisfies the outside equation of that sphere. Since the first equation is valid anywhere within the sphere and since Laplace's equation holds only in regions containing no attracting matter, that portion of the potential representable by the first equation must be due to magnetic matter (or electric currents) located entirely outside the sphere. Similarly that portion of the potential representable by the second equation must be due to magnetic matter (or electric currents) located entirely inside the sphere.

The most general assumption regarding the zonal portion of the Earth's magnetic potential is that it is composed of two portions, W_i, due to magnetic matter within the sphere, and W_e, due to magnetic matter outside the sphere, the combined potential being

$$W_i + W_e = a\Sigma[I_n(a/r)^{n+1} + E_n(r/a)^n]P_n$$

If this potential is differentiated to give the components of the magnetic intensity as explained above, the expressions obtained are

$$\begin{aligned} X &= \Sigma[E_n(r/a)^n + I_n(a/r)^{n+1}](\partial P_n/\partial\theta) \\ Y &= -\Sigma\{[E_n(r/a)^n + I_n(a/r)^{n+1}]/\sin\theta\}(\partial P_n/\partial\lambda) = 0 \\ Z &= \Sigma[nE_n(r/a)^{n-1} - (n+1)I_n(a/r)^{n+2}]P_n \end{aligned}$$

Upon considering only the first zonal harmonic, P_1, at the surface of the Earth, $r = a$, which represents the simplest form of an axially symmetrical field, the components of magnetic intensity become

$$\begin{aligned} X &= [E_1 + I_1]\sin\theta \\ Z &= [E_1 - 2I_1]\cos\theta \end{aligned}$$

(Since the field is axially symmetrical, there is no Y-intensity, the differentials of the P's with respect to λ being zero.) If the average values of X

and Z are known at several selected parallels of latitude, the values of the bracketed expressions, $[E_1 + I_1]$ and $[E_1 - 2I_1]$, may be obtained by averaging or some other suitable means. The values of the bracketed expressions being designated by C and D, respectively, the values of E_1 and I_1 may be obtained by solving the simultaneous equations

$$\begin{aligned}[E_1 + I_1] &= C\\ [E_1 - 2I_1] &= D\end{aligned}$$

thus resolving the field into its internal and external components. If the entire series of zonal harmonic coefficients is to be evaluated, the process becomes the determination of the values of the coefficients which fit the values of the intensity-components best at all the parallels used. In this case it is necessary to resort to least squares or some similar method.

The representation of a magnetic field which is not axially symmetrical requires the use of tesseral and sectorial harmonics which involve λ. There are no tesseral or sectorial harmonics of degree zero, two of degree 1, four of degree 2, etc. A surface tesseral or sectorial harmonic is of the form

$$\sin m\lambda P_{nm} \text{ or } \cos m\lambda P_{nm}$$

the second subscript m designating the order. P_{nm} is the function

$$\sin^m \theta[d^m/(d \cos \theta)^m]P_n$$

One of the sectorial harmonics of the first order and degree is $\cos \lambda \sin \theta$. That portion of the potential which may be represented by one of the first sectorial harmonics may be expressed

$$W = a[E_{11}(r/a) + I_{11}(a/r)^2] \cos \lambda \sin \theta$$

and the components of intensity at the Earth's surface obtained by differentiation are

$$\begin{aligned}X &= [E_{11} + I_{11}] \cos \lambda \cos \theta\\ Y &= -[1/\sin \theta][E_{11} + I_{11}] \sin \lambda \sin \theta\\ Z &= [E_{11} - 2I_{11}] \cos \lambda \sin \theta\end{aligned}$$

Such a potential gives rise to a Y-intensity and the value of the bracketed expression, $[E_{11} + I_{11}]$, may be obtained from the observed values of X alone or of Y alone. If the field is entirely representable by a potential, the values of the bracketed expression obtained from X and from Y must be identical. Failure of the two values to agree within the limits of observational and computational accuracy is evidence that the field has curl. Resolution of the axially unsymmetrical portion of the field into its internal and external components is performed as for the zonal harmonics.

In analyses of the Earth's field the two values for $[E_{11} + I_{11}]$ derived from the observed values of X and Y have not been found to agree. Most investigators have used the mean of the two values to separate the field into its internal and external components. The numerical procedure for the analysis consists of obtaining Fourier coefficients which represent the observed values of X, Y, and Z at selected parallels and from the coefficients of the sine- and cosine-terms so obtained determining coefficients of the various tesseral and sectorial harmonics which fit the data best. The mean values of X and Z for each parallel are disposed of by zonal harmonic analysis. Pairs of harmonics of the same degree and order are sometimes combined into a single harmonic in the final result by the relationship

$$(A \cos m\lambda + B \sin m\lambda)P_{nm} = [C \sin (m\lambda + \alpha)]P_{nm}$$

in which $C^2 = A^2 + B^2$ and $\tan \alpha = A/B$.

The ordinary spherical harmonics used in mathematical and physical papers have the practical disadvantage that their numerical factors vary greatly according to the order, m, of the harmonic. Thus, as defined above, $P_{41} = \frac{5}{2} \sin \theta(7 \cos^3 \theta - 3 \cos \theta)$, while $P_{44} = 105 \sin^4 \theta$. If these two harmonics are of comparable importance, in representing an observed potential, their coefficients will be of different magnitude. Therefore Adolf Schmidt [248] has introduced normalized functions designated by P_n^m which have the property that the mean square value of

$$[\sin (m\lambda + \alpha)]P_n^m$$

over the surface of a sphere is the same for a given degree, n, regardless of the order, m. These normalized functions, P_n^m, are identical with the functions P_{nm} when the latter have been multiplied by

$$\sqrt{\epsilon_m(n - m)!/(n + m)!}$$

in which $\epsilon_0 = 1$, $\epsilon_1 = \epsilon_2 = \epsilon_m = 2$. Obviously, for the zonal harmonics, $(m = 0)$, the normalized functions are completely identified with those described above.

In a series developed in normalized spherical harmonics the importance of each term can be estimated immediately from the magnitude of its numerical coefficient. These functions are being widely adopted for geophysical work. Throughout the remainder of this discussion normalized functions will be used.

III. THE PERMANENT MAGNETIC FIELD OF THE EARTH

(1) General description of the permanent field

To a first approximation the Earth's magnetic field may be considered as due to a small but powerful magnet at the center with its north-seeking pole directed toward the south. This gives rise to the first zonal harmonic shown in Figure 1. The addition of another weaker magnet at the center perpendicular to the first gives rise to the first sectorial harmonic which corresponds to a tilting of the magnetic axis.

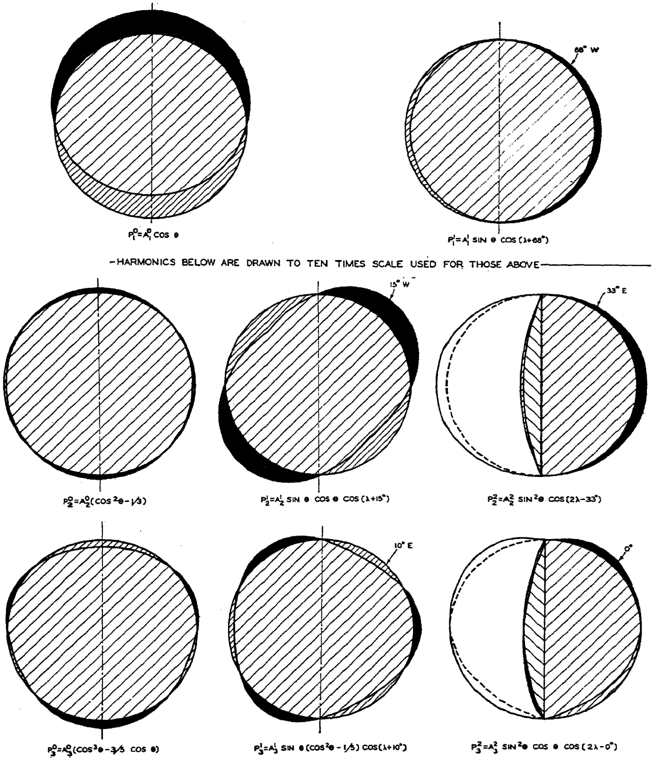

68° W
$P_1^0=A_1^0 \cos\theta$
$P_1^1=A_1^1 \sin\theta \cos(\lambda+68°)$
-HARMONICS BELOW ARE DRAWN TO TEN TIMES SCALE USED FOR THOSE ABOVE-
15° W
33° E
$P_2^0=A_2^0(\cos^2\theta-1/3)$
$P_2^1=A_2^1 \sin\theta \cos\theta \cos(\lambda+15°)$
$P_2^2=A_2^2 \sin^2\theta \cos(2\lambda-33°)$
10° E
0°
$P_3^0=A_3^0(\cos^3\theta-3/5 \cos\theta)$
$P_3^1=A_3^1 \sin\theta(\cos^2\theta-1/5) \cos(\lambda+10°)$
$P_3^2=A_3^2 \sin^2\theta \cos\theta \cos(2\lambda-0°)$

FIG. 1.—Representation first 13 harmonic components of Earth's magnetic field.

Figure 1 is a representation of the principal harmonic components of the Earth's magnetic field. The black portions correspond to northern magnetic potential and the hatched portions to southern. In each case a cross-section of the Earth through the axis and point of maximal potential is shown. Each pair of tesseral or sectorial harmonics of the same degree and order has been combined for simplicity according to the formula mentioned in the preceding section.

Figure 1 is more than a mere diagrammatic representation of the potential. It may be considered as representing for each degree of harmonics the relative density-distribution of magnetic poles over the surface of the Earth which would give the observed field, or the relative number of lines of force entering (black) or leaving (hatched) the Earth, or approximately the vertical intensity at various points. A striking feature brought out by the representation is the dominance of the first-degree harmonics which are drawn to one-tenth the scale of the others. Only the harmonic P_2^1 is comparable with them in magnitude.

Although to one engaged in exact magnetic measurements the Earth's field seems extremely irregular, nevertheless its major features can be closely represented as due to a small but powerful magnet at the center of the Earth whose axis passes through the point $78^{\circ}.5$ north latitude and 291° east longitude known as the geomagnetic pole.

A still closer approximation to the Earth's field [181, 204] is given by assuming it is due to a magnet (dipole) displaced 342 km from the center of the Earth toward a point in longitude 162° east and latitude $6^{\circ}.5$ north with its axis parallel to a line through the center of the Earth and the geomagnetic pole. The superiority of this approximation over that of the centered dipole is not very marked.

Although the representation of the Earth's field by appropriately located magnetic dipoles is convenient, the device must be regarded entirely as mathematical fiction. However, such dipoles do correspond to certain physical realities. The magnetic field resulting from a centered dipole is identical with the field which would result from a uniform magnetization of the substance of the entire Earth or of a spherical and centered core, the direction of magnetization coinciding with the direction of the axis of the assumed dipole. The hypothesis of the eccentric dipole is equivalent to a slightly greater magnetization of the Earth's substance in the region toward which the dipole is assumed to be shifted.

Considering only the first-degree harmonics the total magnetic moment of the Earth may be taken as 8.1×10^{25} CGS units, corresponding to an intensity of magnetization of 0.08 CGS unit per cc for the entire substance of the Earth on the hypothesis of uniformly distributed magnetization. Although this magnetization is several orders of magnitude less than is obtainable in the best magnet steels, it is still many orders of magnitude greater than is observed in ordinary rocks.

A magnetic field identical with that due to a uniform magnetization of the Earth would result from electric currents flowing westward in the Earth parallel to circles of latitude about the axis of uniform magnetization, the density of flow being proportional to sin θ at all points, where θ is the angular distance of a given point from the pole of the axis of magnetization. The eccentric-dipole concept requires a somewhat denser flow in the region toward which the assumed dipole is shifted.

Subtracting the field of either the centered or eccentric dipole from the observed field still leaves large and irregular residuals, amounting to 10,000γ (1 γ = 0.00001 CGS unit) in horizontal intensity over regions millions of km^2 in area. Thus, while the field may be quite closely represented by harmonics of the first degree, extremely high harmonics are necessary for a very complete representation.

These portions of the field which are not representable by low-degree harmonics are called regional anomalies. Less extensive anomalies which cover areas as great as a few km^2 or even hundreds of km^2 are called local anomalies. One of the most notable of these is the anomaly of Kursk [460] in U.S.S.R. situated at about latitude 52° north and longitude 36° east. Here the horizontal component of magnetic intensity varies from 20,000γ to 80,000γ within a distance of two km, declination varies 170° in less than one km, while vertical intensity attains a value of over 200,000γ, three times its value at the magnetic pole.

Sometimes reference is made to the equatorial pole of the Earth's magnetism. This concept regards the harmonics of the first degree separately, the equatorial pole being a mathematical point on the equator at 291° east where the harmonic P_1^1 has its maximal value. If the harmonic P did not exist, this point would be the geomagnetic pole.

(2) GENERAL DESCRIPTION OF THE EXTERNAL AND NON-POTENTIAL FIELDS

The complete results of the analysis of the Earth's magnetic potential are not revealed in Figure 1. Gauss, who first analyzed the field, concluded, in view of the inaccuracy of data then available, that all the observed magnetic force had its origin in the interior of the Earth. None, he believed, was due to a cosmic magnetic field or to magnetic origins above the Earth's surface. More recent and careful analyses employing more accurate data, particularly those of Bauer [184] (1922) and Schmidt [47] (1885), indicate three sources of the observed magnetic force. One, which gives rise to over 94 per cent of the field, is due to causes within the Earth, another to causes outside the Earth, and a third, called the non-potential portion, is such as would be due to vertical electric currents passing through the Earth's surface. Bauer gives for the coefficients of the first zonal harmonics of the internal and external fields 0.31089 CGS unit and 0.00539 CGS unit, respectively. The contribution of the external field to the observed magnetic intensity in general augments the horizontal intensity in equatorial regions and decreases the vertical intensity in polar regions, being of such a character as would be caused by an eastward electric current in outer space flowing around the Earth's axis. The "tilting" of the magnetic axis from the geographic axis is greater for the external field than for the internal field, the ratio of the terms P_1^1 to P_1^0 being one-fourth for the external field and one-fifth for the internal field. The harmonic series representing the external field converges less rapidly than that representing the internal field, which signifies that the former is more complex. This condition may be due in part or entirely to the greater uncertainty of the terms as compared with the relatively small values of the principal terms.

Failure to obtain sufficiently close agreement between the coefficients of the various harmonics as deduced from the X-components and from the Y-components of the magnetic intensity has led various investigators to conclude, at least provisionally, that a portion of the Earth's field is not derivable from a potential. This non-potential portion consists of apparent vortices of magnetic intensity on the surface of the Earth directed, in general, in a clockwise direction in low latitudes and in a counter-clockwise direction in high latitudes. Were the internal and external constituents of the Earth's field removed leaving only the non-potential field, the lines of magnetic intensity would form closed circuits on the Earth's surface such as would be due to a hypothetical current flowing, in general, vertically downward in low latitudes and contrariwise in high latitudes, although its distribution is extremely irregular. The magnitude of this hypothetical current is about 0.2 amp per km^2 at its maximum. A traveler following the compass-direction in this field would return to the starting-point without circumnavigating the Earth.

(3) REALITY OF THE INTERNAL, EXTERNAL, AND NON-POTENTIAL FIELDS

This division of the Earth's field into three portions naturally raises the question of whether the three portions are physical realities or are mere numerical results of mathematical analysis obtained by attempting to adjust uncertain observed values to fit rigorous mathematical formulas. The conclusion that the internal field is real is unquestionable—a few rough magnetic observations at various latitudes establish this fact beyond doubt. Less assurance, however, is attached to the conclusions regarding the external and non-potential portions.

The existence of an external field was not accepted by Gauss since inaccuracies of the data available at the time his analysis was made did not warrant its assumption. Schmidt, employing better data than those available to Gauss and introducing certain refinements in the method of analysis to compensate for the oblate form of the Earth, found reason for believing in its existence. Bauer, who performed an analysis, using the same method employed by Schmidt, and who had at his command the best magnetic data available, obtained even larger values for the external field.

Bauer, in his analysis, took into account additional data from the world-wide magnetic survey conducted by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington including many land expeditions and the several cruises of the magnetic-survey vessels, the *Galilee* and the *Carnegie.*

Dyson and Furner [189], employing much the same data as Bauer, obtained quite different values for the external field according as they confined their data to the regions from 60° north to 60° south or from 80° north to 80° south. (Bauer's analysis was based on data taken between 60° north and 60° south.) For this reason, Furner and Dyson rejected the idea of an external field. Bauer, however, contended that this discrepancy was due to the great uncertainty associated with magnetic observations beyond the 60° parallels and that Furner and Dyson's results justified his utilization of only the lower-latitude data.

Rejection of the idea of an external field on the basis of uncertain or insufficient data does not appear warranted. Errors in measurements of magnetic inclination as great as one degree would be required to explain it on this basis, and these errors would have to be systematic. Furthermore, since there is evidence of an external field in the diurnal and magnetic-storm variations which admits of no doubt, the assumption of similar magnetic origins giving rise to a portion of the permanent field requires no stretch of the imagination.

Less confidence is to be placed in the reality of the non-potential portion. Although it appears comparable in magnitude with the external field, and consequently large errors in the observed magnetic forces would have to be assumed to deny its existence, its apparent distribution does not require that the errors be systematic over the entire Earth.

There is, however, another method of determining the non-potential portion, namely, by taking line-integrals [197], for the Earth's field appears to have curl. In mathematical language, where ϵ is the angle between H and ds and the path of integration is taken along a closed curve on the Earth's surface, we have

$$\oint H \cos \epsilon \, ds \neq 0$$

Line-integrals which have been computed for certain portions of the Earth have indicated the presence of a hypothetical electric current similar in direction and magnitude to that deduced from the potential-analysis. Also, in the absence of a non-potential field, a line around the Earth everywhere perpendicular to the isogons would close. Such lines have been computed and they have not closed by about 60 km on the average. This additional evidence for the existence of a non-potential portion is not to be considered fully corroborative for, being based on the same data as the potential-analysis, it would be surprising if it led to different conclusions.

An attempt to verify this non-potential portion has been made in Japan by taking line-integrals and so evaluating the component of the curl, $\partial X/\partial y - \partial Y/\partial x$, directly. This led to a hypothetical current directed upward on one side of the main island and downward on the other. This irregular distribution of the current is also evident in its world-wide distribution where large areas in the same latitude-belts evince oppositely directed currents. Above all, there is no evidence other than the magnetic observations for believing such a current to exist.

One further aspect of the terrestrial-magnetic field was boldly suggested by Gauss who questioned whether the number of lines of force entering and leaving the Earth were equal. According to present-day data this is not true, that is

$$\int(\partial W/\partial r)dS \neq 0$$

where the integration is over the entire surface of the sphere. Although classical electromagnetic theory does not subscribe to such a view, its possibility must be recognized. It is to be concluded that great inaccuracies exist in the data or that isolated magnetic charges, as suggested by the atomic theorists, do exist. Either conclusion is disconcerting in an analysis of the Earth's magnetic field. Recent magnetic observations in remote regions show that the magnetic charts have been greatly in error in those regions.

(4) THEORIES OF THE ORIGIN OF THE INTERNAL FIELD

The major problem of terrestrial magnetism is to explain the cause of the permanent field. Recognizing that the greatest part of the field originates from causes within the Earth, early investigators conceived the Earth to be a ferromagnetic body. Studies of the interior of the Earth through seismic waves, rigidity- and density-calculations, electric and magnetic phenomena, and other means at our disposal have yielded information upon the plausibility of such a view.

It is generally recognized by geophysicists that the Earth has a core about 3,500 km in radius of density about 12, which is commonly assumed to be nickel and iron compressed by tremendous pressure [1267]. There is a notable difference of opinion as to whether this core is solid or liquid. Except for one fact the existence of this core is favorable to the view that the Earth is ferromagnetic.

Bore-holes in the Earth's crust have indicated an increase of temperature with depth amounting to about 30° per km. Also, the phenomenon of vulcanism points to the existence of high subcrustal temperatures, although these may be purely local effects. Though extrapolating the temperature-gradients observed at the surface in to the center of the Earth is not justified, a high temperature of the interior such that iron or magnetite is above the Curie point at depths greater than about 20 km and 15 km, respectively, seems likely.

The hypothesis of ferromagnetism to explain the Earth's field should not be too readily rejected. Direct knowledge of the temperatures of the interior of the Earth is not available. The temperatures which have been assigned for various depths rest upon numerous assumptions and, in many cases, questionable empirical information. Reappraisal of the surface temperature-gradients deduced from bore-hole data indicates that the temperatures at various depths may be lower than have been supposed. In the absence of more convincing information concerning the temperatures within the Earth, the hypothesis that much of the Earth's substance is ferromagnetic must be provisionally retained [1270].

The possibility that the extraordinary pressures existing in the Earth's interior may raise the Curie point of ferromagnetics has been recognized. Experimental confirmation of this suggestion may not be possible, but experiments conducted with the artificial pressures up to several thousand atmospheres indicate no large change in the Curie point with pressure [179]. These pressures correspond to depths of only 8 to 16 km.

Though ferromagnetism within the Earth is not a thoroughly tenable belief, in the cooler crustal region ferromagnetics undoubtedly could contribute to the Earth's field. Nippoldt has suggested that the entire internal field has its origin in the crust. This would require in the 15-km layer, where, in consideration of interior temperatures, magnetite can be ferromagnetic, about 800 kg per cubic meter, all of which must have about the maximum residual magnetization observed for the substance. Furthermore, the direction of magnetization must at all places be approximately parallel to the magnetic axis of the Earth. In view of the dominance of the first-degree harmonics, it is difficult to believe that the comparatively thin crust can give rise to the entire field. The relative scarcity of iron as an element of the crust further argues against this hypothesis.

Local anomalies have been attributed to large beds of iron ore discovered near-by. The existence of these is sometimes adduced to support the theory of crustal magnetic origins. However, the irregularities to which they give rise rather indicate that such origins cannot explain the permanent field. Though a small mass of magnetic material beneath the Earth's surface may give rise to considerable magnetic vertical intensity above it, the addition of the material laterally, maintaining the same thickness, actually decreases the magnetic force at that point.

Failing to develop an adequate ferromagnetic theory of the Earth's magnetism has led to the proposal of current-theories. Lamb [1268] has shown that an electric current once started in a copper sphere the size of the Earth would require 3,000,000 years to die down to one-half its initial value. The starting of such a current would constitute as great a problem as the field itself. Furthermore, the Earth is not a copper sphere and, even if it were, the magnitude of a current sufficient to cause the present field would have been inconceivably great within geologic time. Computations of the resistivity of the Earth based on currents induced by the diurnal variation give a value of about 10^{12} EMU although it has been pointed out that these calculations pertain only to the outer portions since the period of the diurnal variation is too short to affect the interior. At depths below several hundred km the resistivity is about an order of magnitude less than this, according to the indications of the field-variations during magnetic storms. Recent work of Lahiri and Price [408-*A*] suggests that the resistivity in this region varies approximately as $(r/a)^{16}$.

A new basis for theorizing on the origin of the Earth's field has developed in recent years through Hale's discovery that the Sun appears to have a magnetic field similar to the Earth's [59]. This conclusion is reached because of Zeeman splitting of lines in the solar spectrum. The apparent intensity of the solar field is about 50 gauss at the lowest measurable depths in its atmosphere, the value falling off to about ten gauss 400 km higher. The magnetic axis of the Sun appears to be inclined about 6° to the rotational axis (as compared with $11^{\circ}\!.5$ for the Earth) and the polarity the same as for the Earth with respect to rotation. On this basis the intensity of magnetization of the Sun is slightly less than seven CGS units per cc, nearly two orders of magnitude greater than for the Earth. Determination of the solar magnetic field involves a very difficult technique, such that few observers have been able to verify Hale's findings. The regions of sunspots exhibit strong local fields, amounting to 4,000 gauss, which increases the difficulty of determining the general magnetic field of the Sun.

The close similarity between the terrestrial and the apparent solar magnetic fields suggests that the same mechanism may give rise to both. Larmor [1269] has proposed a hypothesis based upon the internal circulation of matter in the meridional planes of both bodies, which motions induce electric currents in the matter, the circulation being perpendicular to the lines of magnetic force. The magnetic fields thus may have started from insignificant beginnings and, by a process of self-excitation, developed into their present state. This hypothesis requires, of course, a fluid motion of the Earth's interior matter. Cowling [54] has taken exception to this hypothesis and by mathematical reasoning has attempted to demonstrate the impossibility of the self-excitation although Larmor does not admit the contentions as valid.

The Nernst-Ettinghausen effect, in which a crossed temperature-gradient and magnetic field give rise to an electromotive force perpendicular to both, has been invoked by Gunn [190] to explain the permanent magnetic fields of the Earth and the Sun. Assuming, quite reasonably, that the center of the Earth is hotter than its surface, the flow of heat across the magnetic field results in a current in the Earth circulating around the axis. This current in turn sustains the magnetic field. Thus, originating from insignificant beginnings, as in Larmor's hypothesis, the magnetic field is assumed to have built itself up to its present value. No critical examination of this suggestion has been published and ignorance of the Earth's internal condition prevents more than a hypothetical estimate of its quantitative adequacy. The hypothesis is further complicated by involved theoretical considerations.

Attempts to explain the terrestrial and solar magnetic fields as due to the rotation of electric charges have been equally unsuccessful [207, 211]. If the Earth possesses an electrostatic surface or volume-charge, its rotation will produce a magnetic field. This field, if viewed by an observer partaking of the Earth's translatory but not its rotary motion, would be identical in form with the first zonal harmonic observed for the terrestrial field if the charge is negative. Atmospheric-electric observations point to the existence of a negative surface-charge but its magnitude is too small to account for the magnetic effects by a factor of 10^8. Furthermore, as viewed by an observer partaking of the Earth's rotary motion the tangential component of the field would be reversed so that the rotation of surface-charge will in no way account for the effects, the observed magnetic field being in the same direction, relative to cosmic space, at the equator and at the poles.

The difficulties of this hypothesis are somewhat overcome by the assumption that the Earth has both a surface- and volume-charge of equal magnitude but opposite sign. In this way the Earth could be electrically neutral and still possess a magnetic field due to the rotation of the two charges at different equivalent rotation-radii. The electrostatic gradients set up by this separation of charge within the Earth would be so great that no satisfactory mechanism has been conceived which would maintain such a separation of charge.

Resorting to the Lorentz theory of gravitation which postulates that the attraction between unlike charges slightly exceeds the repulsion between like charges, schemes have been developed to account for a charged Earth. However, consideration of the relativity principle leads to the conclusion that the modification of the forces between stationary charges would involve a concomitant modification of the forces between moving charges so that the magnetic field so ingeniously produced would cancel itself.

The possibility that elementary magnets in a rotating body may align their axes with the axis of rotation in the manner of a gyrocompass was suggested by Maxwell. Experimental investigation has demonstrated that such an effect [1258] exists but attempts to account for the Earth's magnetic field in this way fail completely because the magnitude of the effect is too small.

Sheer desperation has led to more speculative endeavors to account for the Earth's magnetism by modifying the classical laws of electrodynamics. The procedure is an unsatisfying one and derives its support from the fact that the magnitude of the modifications is so small that definite disproof of the assumptions is impossible.

(5) THEORIES OF THE EXTERNAL AND NON-POTENTIAL FIELDS

Theories of the external portion involve less difficulty. The form of the field and its comparative constancy relative to geographic coordinates preclude the possibility that it is due to cosmic or solar magnetic fields. Likewise, the absence of suitable matter in the space about the Earth does not permit its ascription to ferromagnetism.

It is natural, therefore, to attribute the external field to ionic movements in the high atmosphere (ionosphere) which may be of two sorts, namely, currents or diamagnetic movements. The positive space-charge of the atmosphere which compensates the negative surface-charge of the Earth would give rise by its rotation to a suitably formed magnetic field, as viewed by a fixed observer, to account for the axially symmetrical part of the external field but its magnitude is many orders too small. Bauer has suggested that the crossed terrestrial-magnetic and atmospheric-electric fields may give rise to the necessary currents. This hypothesis is open to the objection that the electric gradient is practically nil in richly ionized regions. Crossed gravitational and magnetic forces similarly causing a current in the ionosphere have been offered as an explanation by Hulburt [1039].

The fact that ions moving in a magnetic field with their gas-kinetic velocities spiral about the lines of force so as to oppose the field present has been suggested by Gunn [57] as causing the radial limitation of the solar magnetic field. Such effects undoubtedly occur in the ionosphere also, making that region diamagnetic and crowding the lines of force close to the Earth's surface.

Thus, in contrast with the internal field, the external field has a number of possible causes. Any one of these, or the combined effects of all, may be responsible for the field which is observed. The problem of the magnetician is to acquire sufficient information accurately to test the merits of each hypothesis. The difficulty of proposing a suitable theory to explain the non-potential field constitutes one of the strongest arguments against its existence. According to the present known laws of electromagnetics it could be produced only by an electric current flowing perpendicularly to the Earth's surface. The measured atmospheric-electric current is too small by a factor of 10^4 to account for the effect. No experiment yet devised has given evidence of the existence of an appreciable current between the Earth and the air except the magnetic observations.

Highly speculative theories have been proposed to account for the non-potential field—one that it is due to the passage of β particles through the atmosphere at such a high velocity that they produce no ionization; another, that the equation, $\oint H \cos \epsilon \, ds = 0$, does not hold on the surface of a rotating sphere. Both of these theories fail to explain the irregular distribution of the non-potential field. They would be strange β particles indeed which went one direction in Europe and another in America. Laws of electrodynamics would be equally strange if the quantity, $\oint H \cos \epsilon \, ds$, was greater than or less than zero according to whether the observer was in America or Europe. It is far easier to be reconciled to the view that the non-potential field is due to errors of observation, which in many places are known to be large, rather than to some unknown law or fact of nature.

IV. SECULAR VARIATION OF THE EARTH'S MAGNETIC FIELD

A few measurements of the Earth's magnetic field at the same place, but separated in time by several years, suffice to reveal that the Earth's magnetic intensity is changing in magnitude and in direction. However, to give a clear picture of the changes which are occurring, large numbers of observations, considerably separated in space and time, are necessary. Extensive surveys conducted by the local governments over the more civilized portions of the Earth's surface and by the Carnegie Institution of Washington over the regions where such agencies are not active, particularly over the oceans, have partly supplied this need.

Four major aspects of secular change may be considered, namely: (1) Changes in the total magnetic moment of the Earth; (2) changes in the direction of magnetization; (3) irregular changes of apparently local origin; (4) changes in the external field.

(1) Changes in the total magnetic moment of the Earth

Comparing the results of his analysis of the general field for the epoch 1922 with the results of analyses based on earlier data, Bauer found that the Earth's moment had apparently been decreasing at a rate of 1/1,500 per year for the past 80 years. If this apparent change continues, the Earth's moment will be reduced to half its value in about 1,100 years. When extrapolating this change backward through the ages the present value of the Earth's moment, 8.6×10^{25} CGS, might be compared with the values 3.4×10^{26} at the age of Socrates, 5.5×10^{27} at the dawn of history, and 8.0 × 10^{28} at the time of the Cro-Magnon man; and the present value of horizontal force at Washington, D. C., 0.18 CGS, with the corresponding values, 0.72, 11.5, and 160, respectively! The conclusion is obvious. Figure 2 shows the apparent change in the first-degree harmonics on the basis of various analyses.

Bauer, although believing this decrease to be real, did not regard it as constant through all time but rather as a manifestation of a long-period oscillatory variation in the total magnetic moment of the Earth. In this connection it should be pointed out that examination of the magnetization of some igneous rocks reveals that they are polarized oppositely from the prevailing present direction of the local magnetic field [450, 455] and many of the older rocks are less strongly magnetized than more recent ones. On the assumption that the magnetization of the rocks occurred when the magma cooled and that the rocks have held their present positions since that time, this would indicate that the polarity of the Earth has been completely reversed within recent geologic times. Owing to numerous complications, such results should be considered with extreme caution.

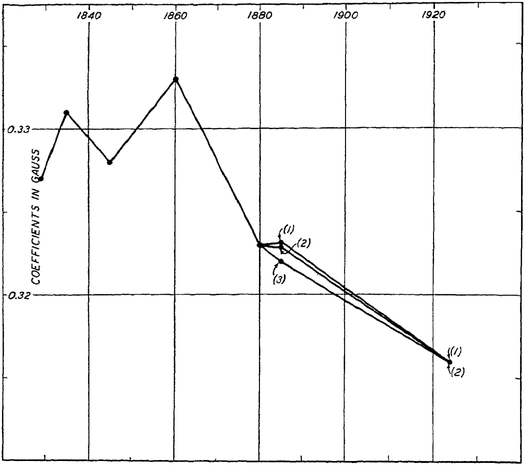


FIG. 2.—Coefficients of harmonic which represents uniform magnetization from different analyses: [Sources: 1829, Erman and Petersen; 1835, Gauss; 1845, Adams; 1860, Carlheim, Gyllensköld; 1880, Adams; 1885, Schmidt (1), Fritsche (2), Neumayer and Petersen (3); 1922, Furner and Dyson (1), Bauer (2).]

Further evidence on a decrease of the Earth's moment has appeared as the result of examination of the changes in the horizontal intensity over various regions of the Earth as indicated by data collected during recent years [346]. These data, although distributed over only a few years, give much more accurate information on the secular variation than the lengthier series involving earlier records. They reveal that regions of decreasing horizontal intensity predominate and that the changes in horizontal intensity during recent years integrated over the Earth's surface are distinctly negative. It is not safe at the present time, however, to draw any very extensive or startling conclusions regarding a trend in the total magnetic moment of the Earth. If the Earth is a very good electrical conductor, which it may be at great depths, its time-constant is so great that induced currents would prevent any wide-spread rapid change in its general magnetization.

(2) REVOLUTION OF THE MAGNETIC POLES

One of the most striking features of secular change is an apparent revolution of the Earth's magnetic poles about the axis of rotation. A chart originally prepared by Bauer and brought up to the present time (see Fig. 13 of Chapter I) shows the simultaneous changes in inclination and declination at London for the past four centuries and at Baltimore and Boston for shorter periods. From a comparison of the results of his analysis for 1922 with those of earlier epochs, Bauer found that the Earth's axis had shifted by such an amount that 15,000 years would be required for the magnetic pole to make one complete revolution about the geographic pole. Inspection of such inclination-declination charts suggests a shorter period, the length of this suggested period differing for different places of observation. Inclusion of the more recent data from Baltimore and Boston indicates a more complex progression of secular change than was indicated by the earlier data.

To make a comprehensive study of the apparent migration of the magnetic poles, Carlheim-Gyllensköld [342] employed spherical harmonics of the form, $\alpha_n^m \cos (m\lambda + \beta_n^m)P_n^m$, in which the terms have their usual significance, β_n^m being a function of time. Employing earlier data in which declination and inclination only were given he found that the non-zonal harmonics were rotating about the axis of rotation with various periods—$T_1^1 = 3{,}147$ years, $T_2^1 = 1{,}381$ years, and $T_2^2 = 454$ years—the subscripts and superscripts referring to the degrees and orders of the harmonics, respectively. Since the form of the harmonics was simplest when referred to the axis of rotation, he concluded that this axis had a definite physical bearing on the phenomenon. Rotation of the pole of the first-degree harmonics about the geographical pole is not very strongly supported by the evidence from various analyses, as shown in Figure 3.

(3) Local effects, foci

Investigation of the fine-structure features of the secular variation led Fisk [343] to the discovery of certain regions called foci where the changes in direction or magnitude of the magnetic field were occurring with extreme rapidity (see Fig. 22 of Chapter I). The rate of change at these centers of activity is sometimes greater than 100γ per year in horizontal intensity and 14′ per year in declination and inclination in middle latitudes.

It is clear that no focus could persist over a considerable period of time without radically altering the Earth's entire field so that it would completely lose its outstanding simplicity. Although data for the study of this fine-structure of secular variation are available only for recent years, lengthy series of observations at certain key-stations demonstrate that the foci are continually expanding, contracting, appearing, disappearing, and shifting. Some of the foci, however, are very long-lived, for example, the one in horizontal intensity over South Africa where the decrease in that element since 1843 has amounted to 6,000γ—roughly two-fifths of its present value. The longitude-distribution of these foci appears correlated with the longitude-distribution of the land-areas of the Earth although no such correlation is apparent in the latitude-distribution.

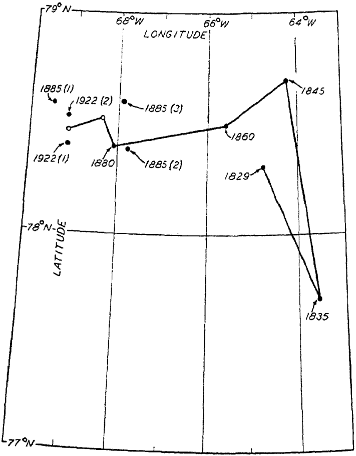


Fig. 3.—Position pole of axis of uniform magnetization from different analyses.

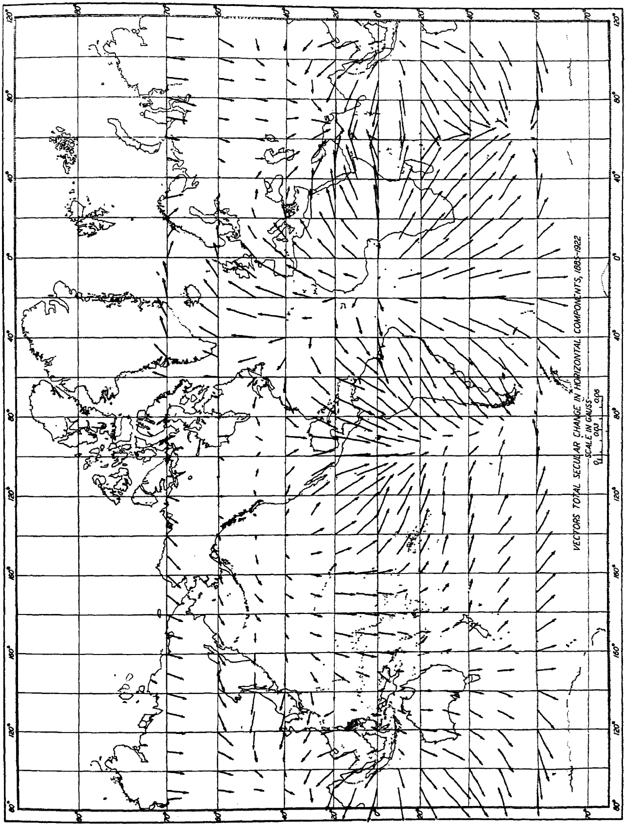


Fig. 4.—Vectors total secular change in horizontal components, 1885-1922.

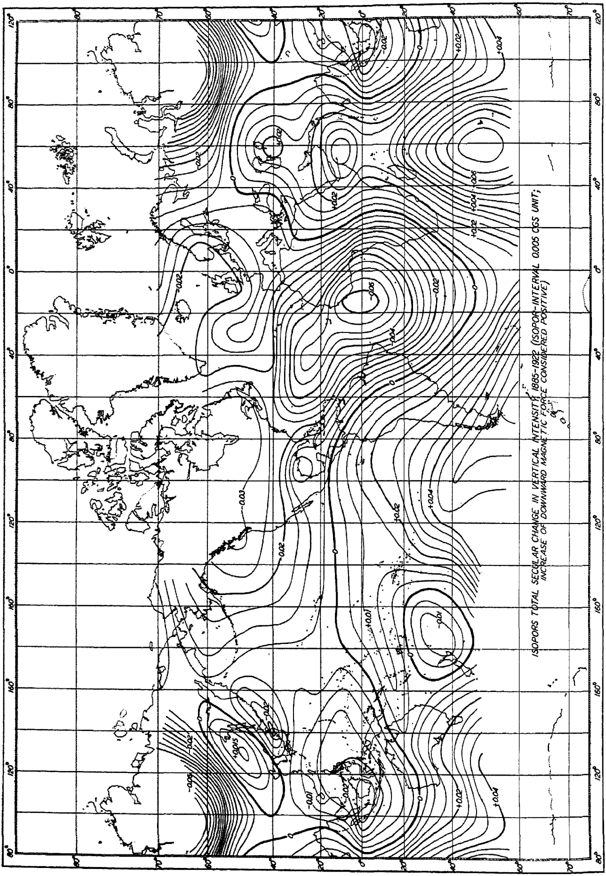

ISOPORS TOTAL SECULAR CHANGE IN VERTICAL INTENSITY, 1885-1922 (ISOPOR-INTERVAL 0.005 CGS UNIT; INCREASE OF DOWNWARD MAGNETIC FORCE CONSIDERED POSITIVE)
-0.02
-0.06
+0.015
-0.01
+0.02
+0.04
-0.03
0
+0.01
-0.01
+0.02
+0.04
-0.06
-0.02
+0.06
+0.22
80°
40°
0°
120°
160°
80°
70°
60°
40°
20°
0°
20°
40°
60°
70°

FIG. 5.—Isopors total secular change in vertical intensity, 1885–1922 (isopor-interval 0.005 CGS unit; increase of downward magnetic force considered positive).

Horizontal components of secular change from 1885–1922 on the basis of data used by Schmidt and by Furner and Dyson in their analyses are shown in Figure 4. Corresponding representation of the vertical component of secular change is given in Figure 5. Special attention is called to a decrease of 6,000 γ off the Guinea Coast—one-tenth the value of the field at the poles.

(4) CHANGES IN THE EXTERNAL FIELD

When very exact data on secular variation, such as are supplied by continually recording magnetic observatories, are examined, the presence of an 11-year cycle in the variations of horizontal intensity superposed on the continual trend of this element is recognizable. Less conspicuous, but still discernible, is an 11-year cycle in vertical-intensity variations. During years of high sunspot-numbers, horizontal intensity passes through a minimum and vertical intensity a maximum, the effect in horizontal intensity being most pronounced at the equator. The distribution of variations in vertical intensity is less clearly defined but appears to be more pronounced in higher latitudes. Such a distribution indicates that the 11-year variations are due to causes outside the Earth's surface [353]. Since, on the average, horizontal intensity is decreased and vertical intensity increased during magnetic storms, the 11-year variation may be attributable to these phenomena, which are more frequent at times of sunspot-maxima.

Simplification of the phenomenon of secular variation has met with little success. Bartels [335] endeavored to represent the relatively accurate secular-change data from 14 continuously recording observatories by a spherical-harmonic series but found the convergence of the series very poor—much poorer than that for the permanent field—indicating the pronounced regional character of secular variation. Furthermore, the principal terms in the series representing the annual change at the observatories do not agree with the change in the same terms in the series representing the general field as determined from analyses for different epochs. From this fact it is concluded that the different results given by these various analyses of the general field arise not from a change in the Earth's field alone but also from the inclusion of different data, the more recent data being more complete and accurate than the older.

The local magnetic constant devised by Bauer has been used by Nippoldt [354] to simplify the study of the secular change. Assuming that the Earth's field arises from a doublet at the center, the components of intensity at any point are $H = M \sin \theta$ and $Z = 2M \cos \theta$ so that $M = \sqrt{H^2 + Z^2/4}$. The value of M obtained in this way from the components of the intensity at a given place is called the local magnetic constant, designated by G. Since secular change seems to involve mainly the higher harmonics of the Earth's field, the significance of changes in G is questionable.

(5) THEORIES TO EXPLAIN SECULAR CHANGE

Since secular change is large relative to the Earth's general field, it follows without need of mathematical analysis that, since the non-potential and external portions of the field are small, the secular change must occur largely through changes in the internal field. This does not preclude the possibility that secular variation may result from causes external to the Earth.

It has been wisely remarked by a number of investigators that any theory of the general field must also allow for secular variation. This does not prevent the development of theories of the secular variation which may be independent of any theory of the general field.

In addition to producing an 11-year cycle in the variations of the magnetic field, magnetic storms may affect the general field in another way. Chapman [376] has pointed out that, although a decrease in horizontal intensity is a characteristic effect of magnetic storms in low and middle latitudes, magnetic flux through the Earth is actually increased during these disturbances and consequently they may play a part in changing the magnetization of the Earth. Thus a slight portion of the flux-increase due to a storm might remain, causing, as the result of many storms, a gradual increase of the Earth's magnetization or change of its direction. An investigation of the results from a number of widely distributed magnetic observatories fails to reveal any such effect; that is, after a period when magnetic storms have been numerous the magnetic elements at each observatory are the same as they would have been had the storms been few [353]. In this respect the Earth behaves as if its hysteresis-loss is zero for the present intensity of magnetization.

To explain the apparent rotation of the magnetic poles about the rotational axis, Carlheim-Gyllensköld and Schuster [205] independently suggested that the space about the Earth might be electrically conducting and by induction exert a retarding effect on the rotation. In this way the magnetic field might rotate with the Earth but at a slightly less angular velocity, giving rise to a slow westward displacement of the magnetic poles relative to the geographic coordinates. As speculative as this hypothesis may have been twoscore years ago, the presence of a conducting region of the Earth's atmosphere—as demonstrated by radio phenomena—which may tend to have a westward drift relative to the Earth's rotation, renders the hypothesis more probable.

On the basis of Larmor's hypothesis to explain the general field, secular variation would be attributed to a change in the channels of circulation of the Earth's interior with a consequent change in the flow of the electric currents. Electric currents produced within the Earth by the motion of various portions of the body across the general magnetic field during isostatic adjustments have been proposed by Gunn to explain the secular variation. His quantitative treatment of this hypothesis indicates that it is inadequate.

The strongly regional character of the foci of secular change indicates that these foci are due to local changes located at no very great depth beneath the Earth's surface. It is possible that they represent a phenomenon completely distinct from the more general features of secular change such as the apparent westward drift of the magnetic poles. Their apparently superficial origin indicates that they may be due to changes in magnetization of the crust. One way in which such changes of magnetization could occur is through a rising or falling of the isotherms so that magnetic material at a temperature near the Curie point would gain or lose its magnetism as the Curie-point isotherm sinks below or rises above it. The quantity of magnetic material required to account for some of the larger foci presents a difficulty for this hypothesis unless the crustal layer capable of ferromagnetism is considerably thicker than 15 or 20 km. The apparent association of foci with continental areas indicates that these foci may be associated with crustal adjustments.

Probably the most complete portrayal of the phenomena of secular variation is offered by a hypothesis of Adolf Schmidt [357]. He assumes that in addition to a dominant permanent magnetization of the Earth there exists a portion of the field, S, consisting of the field due to a uniformly magnetized core and the field due to magnetization induced in the Earth's outer structure by the field of the core. This core he assumes to be slowly rotating with respect to the remaining portion of the Earth. The axis of magnetization and the axis of rotation of the core do not coincide. That component of magnetization of the core perpendicular to its axis of rotation causes changes in the field at the surface.

With the data from London and Paris and from Capetown for changes in inclination and declination over long periods, the moment and axis of rotation of the hypothetical core are computed. The axis of the core intercepts the Earth's surface in about 39° north latitude and about 0° longitude. Its moment is about one-fifth the moment of the entire Earth and its period of rotation about 480 years.

This hypothesis explains at once the apparent diminution of the Earth's magnetic moment noted by Bauer and the inclination-declination charts produced by him from the old observations. Implied in the hypothesis is the possibility that the regions of high secular activity called foci may arise through differences in the permeability of various portions of the Earth's crust. The agreement between the observed values of the

Earth's field and those computed on the basis of this hypothesis is less satisfactory for recent years than for earlier years.

Although this hypothesis has no other evidence than the magnetic to support it and although its physical reality is difficult to countenance, its excellence as a purely hypothetical model warrants careful consideration. In accordance with it, the first zonal harmonic of the Earth's permanent field reached a maximum about 1840—epoch of the first analysis—will pass through a minimum about 2080, and will experience its most rapid change around 1960. The effect which such changes may have on other phenomena, for example, cosmic-ray intensity, is a speculation which encourages long-continued observations of the phenomena.

V. THE SOLAR AND LUNAR DIURNAL VARIATIONS OF THE EARTH'S MAGNETIC FIELD

Although the problems of the permanent field and its secular variation are profound riddles which have so far defied all attempts at satisfactory explanation, the problems of the solar and lunar diurnal variations have been more amenable. The reasons for this are patent. The former have their origin principally, or entirely, within the solid substance of the Earth about which our knowledge is meager and equivocal, while the latter originate largely in the Earth's outer atmosphere, some information about which may be apprehended. A portion of the diurnal variation originates within the Earth, but that portion is due to currents induced by the primary external portion. Furthermore, the changes in the permanent field, if they are cyclic, require apparently centuries or millenniums for their recurrence, so that even one complete cycle has never been observed, while the diurnal variations are so rapid that over 20,000 successive cycles have been recorded by single observatories.

(1) Description of solar diurnal variation in low and middle latitudes

Since the solar diurnal variation, which will be referred to by the letter S, is markedly different in low and middle latitudes, as compared with polar regions, it is necessary to consider variation in the two regions separately. The diurnal variation in low and middle latitudes is, to a fair approximation, a function of local time and geographic latitude. A somewhat idealized representation of the variation in the several components of the magnetic intensity at different latitudes is shown in Figure 6.

Although the average diurnal variations observed at stations in the same latitudes are strikingly similar, certain local peculiarities are obvious which appear to be associated with the locations of the observatories with respect to continental and oceanic areas and irregularities of the Earth's permanent magnetic field. Diurnal variations characteristic of a given observatory are subject to further classification. On magnetically quiet days—that is, days during which the magnetic elements vary smoothly—the average variation is distinctly different from the average variation observed on those days during which the variation progresses irregularly. Because magnetically quiet days are more frequent than disturbed days, variations based on the observations on all days closely resemble the variations on quiet days and hence discussion of the quiet-day variation is applicable in general to all-day averages. Disturbed-day variations, being more closely connected with magnetic storms, will be discussed later under that heading.

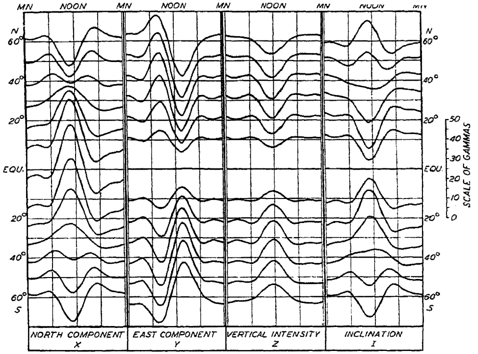


FIG. 6.—Diurnal variation in components of magnetization and in magnetic inclination at various geographic latitudes, all days, sunspot-minimum year 1902, from Chapman's analysis (*after Bartels*).

The quiet-day variation exhibits seasonal changes which consist roughly of an enhancement of the variation in the Northern or Southern Hemisphere during the corresponding local summer. Even in the quiet-day variation the effect of the 11-year cycle in sunspots is evident. At times of sunspot-maxima the amplitude of the variation, even on quiet days, is about 50 per cent greater than at times of sunspot-minima. These increases in amplitude associated with the maxima of the sunspot-cycle are accompanied by slight changes in the characteristic variations at each observatory.

Except for the changes associated with the sunspot-cycle, the variation at any given observatory is substantially the same from year to year and is characteristic of the whole region about the observatory. One outstanding exception to this is exhibited at the Huancayo Magnetic

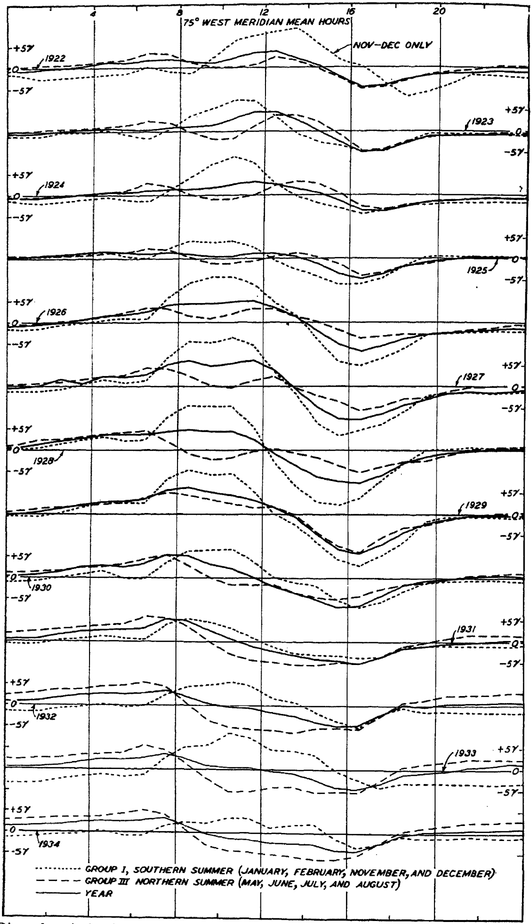


FIG. 7.—Diurnal variation in vertical intensity, Huancayo Magnetic Observatory, five international quiet days, 1922–34.

Observatory [315], situated 12° south of the geographic equator but close to the geomagnetic equator, in a region where the secular variation of the permanent field is very rapid. A change has occurred in type of the average vertical-intensity variation at this Observatory during recent years, as shown in Figure 7. In 1922 the average vertical-intensity variation on quiet days during northern summer was characteristic of the Southern Hemisphere. Gradual changes in the character of the variation took place so that by 1932 the quiet-day variation during northern summer was characteristic of the Northern Hemisphere. These changes were evident, although less conspicuous, in the variations for the other seasons. It is interesting to note that the magnetic equator was closest to Huancayo in 1922 but shifted southward rapidly during the ensuing years, causing the Observatory to be well within the Northern Hemisphere, magnetically, at the end of this series, although it was in the Southern Hemisphere, magnetically, shortly before the observations were begun. The absolute value of vertical force was 324γ in 1922 and $1{,}021\gamma$ in 1932.

Although the average magnetic variation at any one observatory is fairly constant from year to year, considerable differences may exist between the variations on individual quiet days. Amplitudes may vary over wide ranges and at times even the character of the variation may change, maxima occurring at times when minima are to be expected. Such changes may occur in the variation in one component of the magnetic intensity alone or in several. In general, successive quiet days tend to be much alike.

(2) GEOGRAPHICAL DISTRIBUTION

The general geographical distribution of the diurnal variation may be comprehended most readily by consideration of the average variations in the individual components of the magnetic intensity, X (northward), Y (eastward), and Z (radially inward), separately. At the equator the greatest variation occurs in X, the element beginning to increase at about 6^h local time, attaining a maximum shortly before noon, and then sinking toward a minimum shortly before 18^h, the range being about 40γ to 60γ. The range of the variation decreases with increasing north and south latitude. At about 40° north or south a slight depression appears at the maximum of the variation which is accentuated at higher latitudes. At about 60° the variation is the inverse of that at the equator, the range being about 20γ to 30γ.

Variation in the Y-component is negligible at the equator. An increase of intensity toward the east, north of the equator, and toward the west, south of the equator, begins at about 4^h local time and attains a maximum at about 8^h, after which it rapidly decreases, passes its average value shortly after 10^h, and then increases rapidly in the opposite direction. The maximum in the opposite direction—west, north of the equator, and east, south of the equator—is attained at about 14^h, after which the force returns to its average value reached shortly after 18^h. This second movement represents a greater departure from the average value than the first movement. The maximum range, 35γ to 50γ, occurs at about 50°. Since this Y-variation gives rise to the diurnal variation in declination, the two are substantially similar. However, as the variation in declination is given roughly by the formula

$$\Delta D = \Delta Y/X$$

and as the value of X, due to the permanent field, decreases with increasing latitude north or south, the increase of amplitude with respect to latitude for the variation in declination is still more pronounced.

Variation in the Z-component is likewise negligible at the equator. In middle latitudes a decrease in the numerical value of vertical intensity (an *algebraic decrease* north of the equator and an *algebraic increase* south of the equator) begins to occur at about 6^h local time, attains a maximum shortly before noon, after which a return to the night-value, reached shortly before 18^h, occurs. The maximum variation occurs at about 40° where the range is 12γ to 18γ.

Some conception of the local differences in the diurnal variation at stations in similar latitudes may be derived by comparing the average diurnal variation on quiet days for the time of equinox at Huancayo (latitude 12° south) and Apia (latitude 13°.8 south). The range in H at the former station was 106γ for this season in the sunspot-minimum of 1923, while the corresponding range at the latter station was 32γ. The difference is less astounding when it is recognized that the geomagnetic latitude [195] of Huancayo is $-0°.6$ while for Apia it is $-16°.0$. On the other hand, the variations at Cheltenham (latitude 38°.7 north) are quite similar to the variations at Seddin (latitude 52°.4 north) in spite of a difference of nearly 14° in latitude. The geomagnetic latitudes of these two stations (50°.1 and 52°.5, respectively), however, are nearly the same. This outstanding irregularity of the diurnal-variation distribution is manifest in a general southward displacement of the systematic distribution of the variations around the 291°-meridian where the geomagnetic latitude differs greatly from the geographic latitude.

Another striking irregularity in the geographical distribution of magnetic variation is revealed by the study of the diurnal variation in vertical intensity on single days at near-by stations [446]. Although the average curves and most of the individual curves are very similar on certain days, the variation is quite different for stations only a few hundred km apart. It seems that these local differences may be accounted for by irregularities of air-currents in the region of the atmosphere where the diurnal variation has its primary origin.

(3) SPHERICAL HARMONIC ANALYSIS OF SOLAR DIURNAL VARIATION

Numerous attempts have been made to represent the solar diurnal variation as a series of spherical harmonics, as was first done by Gauss for the permanent field, and to separate it into two portions—one arising from origins within the Earth and one arising from causes outside the Earth. Assuming that the variation is solely a function of latitude and local time and is derivable from a scalar potential, that potential should be completely representable by a series of non-zonal harmonics of the form

$$W = a\{[E^m_{na}(r/a)^n + I^m_{na}(a/r)^{n+1}] \cos mt' + [E^m_{nb}(r/a)^n + I^m_{nb}(a/r)^{n+1}] \sin mt'\}P^m_n(\theta)$$

in which t' is the local time given by $(t + \lambda)$ where t is the time at the meridian from which λ is measured. The potential function thus represents a potential in the space surrounding the Earth which does not partake of the Earth's rotation but, while still coaxial with its rotation, remains constantly oriented in space relative to the plane containing the rotational axis and the Sun.

The first analysis of the solar diurnal variation was performed by Schuster [327] to test a hypothesis proposed by Balfour Stewart [50] in 1882. Schuster found that the major part of the variation arose from causes outside the Earth. Numerous other analyses have been performed, all of which have led to substantially similar findings. The earlier analyses employed inadequate data, some of quite questionable accuracy. The distribution of observatories supplying data was quite irregular, leaving considerable areas of the Earth's surface unrepresented, and in many cases the data were for different periods.

The most comprehensive analysis was performed by Chapman [282] using data from 21 widely separated observatories for the years 1902 (sunspot-minimum) and 1905 (sunspot-maximum). The data used were based on all days of the months. Seasonal groups of months were formed as follows: November, December, and January; February, March, and April; May, June, and July; and August, September, and October. In present-day practice the months are grouped as follows: November, December, January, and February; May, June, July, and August; and March, April, September, and October. The data were also averaged according to latitude-belts and the harmonics were selected to fit best the west-intensity and vertical-intensity variations, symmetry being assumed with respect to the equator in the case of the equinoxes and asymmetry relative to the equator in the semi-difference [(summer minus winter)/2]. The parameters of the potential function for the average of the two and for half the difference of the two seasons are shown in Table 1 for the sunspot-minimum year, 1902, and the sunspot-maximum year, 1905, the parameters being defined by the equations

$$E^m_{na} \cos mt' + E^m_{nb} \sin mt' = C^m_{ne} \cos (mt' + \alpha^m_{ne}), \text{ etc.}$$

the time, $t' = 0$, being taken as local-time noon. Chapman's recalculated coefficients are given here since he has abandoned the notation of his original memoirs in favor of Adolf Schmidt's normalized spherical harmonics.

TABLE 1.—*Amplitudes and phase-angles of magnetic solar diurnal variations* (*after Chapman*)
(Unit is 1 $\gamma = 10^{-5}$ CGS unit; time-origin is local noon)

m	n	External		Internal		(C^m_{ni}/C^m_{ne})	$(\alpha^m_{ni} - \alpha^m_{ne})$
		C^m_{ne}	α^m_{ne}	C^m_{ni}	α^m_{ni}		
Mean solstice [(summer plus winter)/2] for 1902							
1	2	4.99	30°	1.68	50°	0.34	20°
2	3	2.94	27	1.32	45	0.45	18
3	4	1.20	42	0.50	53	0.42	11
4	5	0.26	54	0.08	78	0.32	24
Mean solstice [(summer plus winter)/2] for 1905							
1	2	7.13	22	2.56	25	0.36	3
2	3	3.87	20	1.70	39	0.44	19
3	4	1.66	35	0.60	55	0.36	20
4	5	0.37	42	0.16	57	0.43	15
Solstitial inequality [(summer minus winter)/2] for mean of 1902 and 1905							
1	1	3.20	23	1.30	30	0.41	7
2	2	1.77	61	0.76	69	0.43	8
3	3	0.87	87	0.44	119	0.50	32
4	4	0.35	182	0.21	212	0.60	30
1	3	1.78	341	0.66	338	0.37	− 3
2	4	0.71	17	0.36	48	0.51	31

Note: Normalized spherical harmonics after Adolf Schmidt apply to this Table.

As may be seen from Table 1, the ratios of amplitudes of the internal and the external harmonics are always less than unity and the phase-angles for the internal harmonics are greater than those for the corresponding external harmonics in nearly every case, indicating that the internal field leads the external field in phase. The amplitudes and phase-angles for the mean equinox are nearly the same as for the mean solstice, even the irregularities in the amplitude-ratios and the phase-differences being largely reproduced. For the sunspot-maximum of 1905 the amplitudes are about 1.5 times as great, some differences also appearing in the phase-angles. It is striking to note that for each of the components of the diurnal variation—24-hour, 12-hour, etc.—only one spherical harmonic was used in the mean solstice and the mean equinox, its degree being $(m + 1)$. In spite of this simplicity the calculated magnetic variation for each latitude-zone differs from the observed by about only 25 per cent for the three components of force, owing largely to local irregularities in the character of the variations and possibly also to inaccuracies in observing them. One reason for the simplicity with which the harmonics were chosen lies in the grouping of the stations by latitude-belts. For example, the shift from low-latitude to high-latitude type in the north-intensity variation occurs above 40° in the Eastern Hemisphere while it occurs at about 30° in the Western Hemisphere. This grouping tends to smooth out changes in the variation with latitude so they may be fitted with lower-order harmonics. The anomalously large variation in the north component of intensity, discovered at the Huancayo Magnetic Observatory [313], was not known at the time the analysis was made.

After attention was called to the large variation at Huancayo, an analysis of the variations observed on internationally selected quiet days during the equinoxes of 1923 at five stations close to the 285°-meridian ranging from 43°8 north to 31°7 south of the equator was made by McNish [316]. For the purpose of analysis it was assumed that these stations are representative for their respective latitudes and that the variation is a function of geomagnetic latitude and geomagnetic time. To represent the data fairly it was necessary to carry higher-order harmonics.

The relative ratios of the internal and external harmonics and the phase-differences were found to agree substantially with those derived from the analysis of a world-wide distribution of observatories. However, the analysis revealed that the numerical value for the potential of the variation in the Western Hemisphere is over twice as great south of the equator as it is north of the equator and that there is a general southward displacement of the variation in the Western Hemisphere amounting to about 10° of latitude.

(4) THE LUNAR DIURNAL VARIATION

In many ways the magnetic lunar diurnal variation, designated by L, is substantially similar to the solar diurnal variation. Being but about one-fifteenth as great as the latter, it is not evident in the daily records, from which it is derived only with great difficulty by using statistical methods. Since the lunar day consists of approximately 25 solar hours and since the magnetic records are tabulated according to solar hours, the customary method of deriving L at an observatory is to order the solar hours into sequences of 25, the first hour of which being one including some particular lunar hour-angle. But, since the lunar day consists actually of 24 hours and 50 minutes of mean solar time, the first hour of the sixth of such 25-hour sequences would not include the chosen lunar hour-angle. This is compensated by repeating as the first hour of the sixth sequence the last hour of the fifth sequence. Because of the difference of period, S is eliminated in any sufficiently long lunar series. For certain purposes it is advantageous to eliminate S from the tabulated hourly values first by subtracting from each hourly value the monthly mean value of S for that hour.

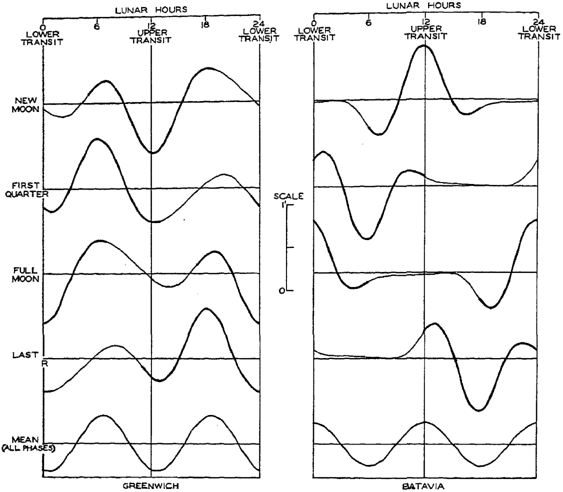


FIG. 8.—Lunar diurnal variation east magnetic declination in summer.

The most significant difference between L and S is that, while S remains fairly constant from day to day, on the average, L varies progressively through the month as shown in Figure 8. Of the various harmonic components of L only the semidiurnal wave remains constant in phase and amplitude throughout the month. Chapman [282, 284] has shown that the phase-angles of all components except the second change progressively with the solar time of the Moon's culmination, the change being $-30°$, $+30°$, and $+60°$ per solar-hour change in the time of lunar culmination for the first, third, and fourth components, respectively, the amplitudes of the waves remaining constant. From another point of view, it may be considered that the components of L other than the second have

TABLE 2.—*Amplitudes and phase-angles of magnetic lunar diurnal variation, mean* 1897–1903 (*after Chapman*)

(Unit is $1\gamma = 10^{-5}$ CGS unit; time-origin is upper culmination of Moon at epoch of new Moon)

m	n	External		Internal		(C_{ni}^m/C_{ne}^m)	$(\alpha_{ni}^m - \alpha_{ne}^m)$
		C_{ne}^m	α_{ne}^m	C_{ni}^m	α_{ni}^m		
Mean solstice [(summer plus winter)/2]							
1	2	0.38	101°	0.14	124°	0.36	23°
2	3	0.38	83	0.21	112	0.56	29
3	4	0.17	106	0.06	125	0.37	19
4	5	0.05	121	0.02	173	0.37	52
Solstitial inequality [(summer minus winter)/2]							
1	1	0.42	72	0.18	103	0.42	31
2	2	0.51	77	0.27	83	0.53	6
3	3	0.21	94	0.11	106	0.53	12
4	4	0.02	110	0.01	93	0.36	−17

Note: Normalized spherical harmonics after Adolf Schmidt apply to this Table.

periods not simply commeasurable with the lunar day, the periods being approximately $\frac{29}{27}$, $\frac{29}{89}$, and $\frac{29}{120}$ lunar day for the diurnal, terdiurnal, and quartidiurnal components, respectively. The physical interpretation of this phenomenon is that the basic lunar variation is a semidiurnal wave of constant phase which is intensified during the hours of daylight.

The lunar diurnal variation, like the solar diurnal variation, has been subjected to spherical harmonic analysis and resolved into the portions due to internal and to external causes. It was found that L arises principally from external causes, that portion due to internal causes being of such a nature as would arise from secondary currents induced in the Earth by the primary external portion. The spherical harmonic coefficients of the lunar diurnal variation deduced from observations during seven years at Pavlovsk, Pola, Zi-ka-wei, Manila, and Batavia, are shown in Table 2. Owing to the phase-change of the harmonics of order other than two, the phase-angles given in Table 2 are reduced to the epoch of new Moon. The coefficients C_n^m have been recalculated by Chapman in order to use the more convenient normalized spherical harmonics of Adolf Schmidt.

Several special features of the lunar diurnal variation are of particular interest from theoretical considerations. The Moon's distance from the Earth varies from time to time. Chapman found that the magnitude of L varies correspondingly, the magnitude being roughly proportional to the inverse cube of the lunar distance. The actual change in L from apogee to perigee amounts to 33 per cent while the time-producing force of the Moon, governed by the inverse cube of the distance, varies 37 per cent for the corresponding times. Associated with this amplitude-change are certain phase-changes in the various harmonics.

(5) THEORY OF THE SOLAR AND LUNAR DIURNAL VARIATIONS

The most satisfactory theory of the magnetic solar diurnal variation is that proposed by Balfour Stewart in 1882. It attributed the variation mainly to horizontal electric currents flowing in the upper atmosphere caused by the tidal motions of the air at right-angles to the vertical component of the Earth's permanent magnetic field. At the time this theory was proposed there was no evidence tending to show that the upper atmosphere could conduct an electric current so that this hypothesis constituted the first scientific assumption of what is now known as the ionosphere, the existence of which has since been demonstrated by radio reflections by Breit and Tuve [992], by Taylor and Hulburt [1104], and by Appleton and Barnett [950]. A few years after this hypothesis had been ventured, when experiments with discharge-tubes had demonstrated the conductivity of gases, Schuster developed the technical details of this theory which have persisted with little alteration down to the present.

The principal uniform motion of the atmosphere involved is a semi-diurnal oscillation probably due to both gravitational and thermal expansion forces caused by the Sun, coupled with resonant phenomena of the atmosphere. (The velocity of sound and the surface rotational velocity of the Earth are nearly the same in middle latitudes.) The air-motions associated with this tide are not subject to the pressure gradient-wind relationships which obtain for ordinary meteorological conditions but are related to the pressure-changes in a manner similar to that applying for ordinary wave-motions, namely, the maximum velocities (westward) occur at times of maximum pressure and are codirectional with the propagation of the pressure-wave, while the minimum velocities—which are negative—occur at times of minimum pressure and are anti-directional with the propagation of the pressure-wave. To a first approximation the velocities are derivable from a potential ψ, known as a velocity-potential, simply related to the pressure-wave by the equation

$$d\psi/dt = v^2 \delta p/p$$

in which v is the velocity of sound, δp, the pressure-change, and p, the normal or average pressure.

The quantity, δp, has been observed at many points on the Earth's surface. Adolf Schmidt has found the pressure-distribution to be closely representable by the spherical harmonics, P_2^2 and P_4^2. The form of the pressure-wave adopted in Chapman's extension of Schuster's study is

$$\delta p = (AP_2^2 - BP_4^2) \sin [2(\lambda + t') + 154^\circ]$$

the values of A and B being determined from observations on the semidiurnal variations in barometric pressure. The velocity-potential deduced from this expression for δp is

$$\psi = \int \delta p dt = (Nv^2/2\pi p)[(A/2)P_2^2 - (B/2)P_4^2] \cos [2(\lambda + t') + 154^\circ]$$

where N is the number of sec in a day.

The velocity of the air is given by

$$u_N = d\psi/ad\theta \text{ (northward)}$$
$$u_E = d\psi/a \sin \theta d\lambda \text{ (eastward)}$$

and the induced electromotive forces by the vector-products

$$\mathrm{EMF}_E = -u_N \times Z \text{ (eastward)}$$
$$\mathrm{EMF}_N = u_E \times Z \text{ (northward)}$$

These electromotive forces vary from point to point and from time to time. At the magnetic equator where the magnetic vertical force is zero the electromotive forces are likewise zero. Remembering the conventions for vectors, it may be seen that if one faces in the direction toward which the air moves the induced electromotive force in the Northern Hemisphere will be to one's left, the first vector-product being negative.

The atmospheric air-motions of the semidiurnal atmospheric tide are shown for a portion of the Earth in Figure 9, and the resulting electromotive forces, assuming a uniform value of vertical force along each parallel of latitude, are shown in Figure 10. In general the electric currents in equatorial regions are driven by the electrostatic field set up to preserve continuous current-flow; this current flows against the applied electromotive force given by direct dynamo-action, except apparently within the anomalous region near the equator in the Western Hemisphere.

If the magnetic variations arise from currents in the atmosphere, the current-function, that is, the scalar potential whose space-derivative is the current-flow, is given by a series of the form

$$\rho = -a\sum_n \sum_m^n [(2n + 1)/4\pi(n + 1)][r/a]^n P_n^m [E_{na}^m \cos mt' + E_{nb}^m \sin mt']$$

in which ρ is the current-function, r is the distance of the current-sheet from the Earth's center, and the E's are the coefficients of the external harmonics derived from the magnetic variation. The expressions

$$i_E = d\rho/rd\theta \text{ (eastward)}$$
$$i_N = d\rho/r \sin \theta d\lambda \text{ (northward)}$$

give the components of current-flow in the two directions in the surface of the current-sheet, i being the product of the current-density and the thickness of the current-layer, which may be assumed as very thin.

The electromotive forces caused by the air-motions may be separated into two constituent parts

$$\mathrm{EFM}_E = -dS'/r \sin \theta d\lambda - d\rho/r\sigma d\theta$$
$$\mathrm{EMF}_N = dS'/rd\theta - d\rho/r\sigma \sin \theta d\lambda$$

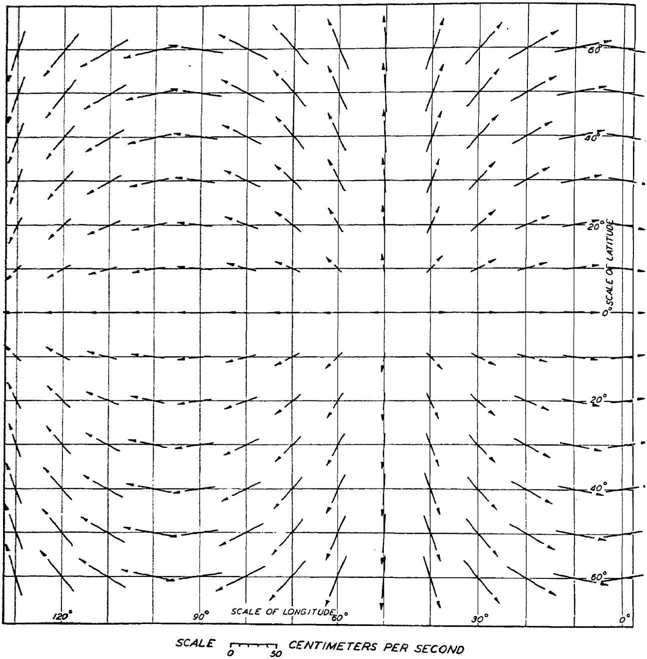


FIG. 9.—Air-velocities arising from semidiurnal atmospheric tides in Western Hemisphere at 11^h, 75° west meridian mean time, typical of those occurring anywhere at the same local time.

the first terms on the right-hand sides being electrostatic gradients which cause the currents to flow in regions where the induced electromotive forces are weak or are opposed to the flow of a continuous current, the second terms representing the potential-drops due to current-flow. The total conductivity of the layer, namely, the specific conductivity multiplied by the thickness, is designated by σ.

It is possible to treat these equations so that S' is eliminated. Writing in the values of the electromotive forces in terms of the velocity-potentials and the Earth's vertical field, all expressed as spherical harmonics, leads to a solution of ρ, the current-function, in terms of spherical harmonics, the principal term of which is a semidiurnal term. A map of this current-system deduced from observed magnetic variations is shown in Figure 11.

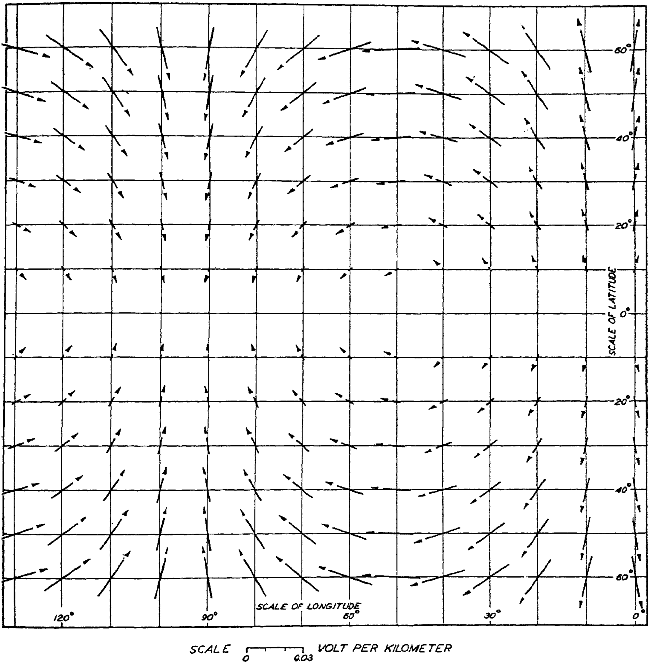


FIG. 10.—Electromotive forces in atmosphere of Western Hemisphere caused by semidiurnal atmospheric tides at 11^h, 75° west meridian mean time, vertical magnetic force being assumed constant along each parallel of latitude.

It is known that the principal term in the empirical current-function is the 24-hour term. If, however, the conductivity, σ, of the layer is assumed to be a function of the Sun's zenith-angle so that the conductivity on the daylight-side of the Earth is very much better than on the night-side, new harmonics are introduced which conform closely in relative magnitude for assumed laws of the conductivity with the observed terms. Such a zenith-angle law is in accord with the well-established fact that ions to which the conductivity is due are produced by some form of solar radiation.

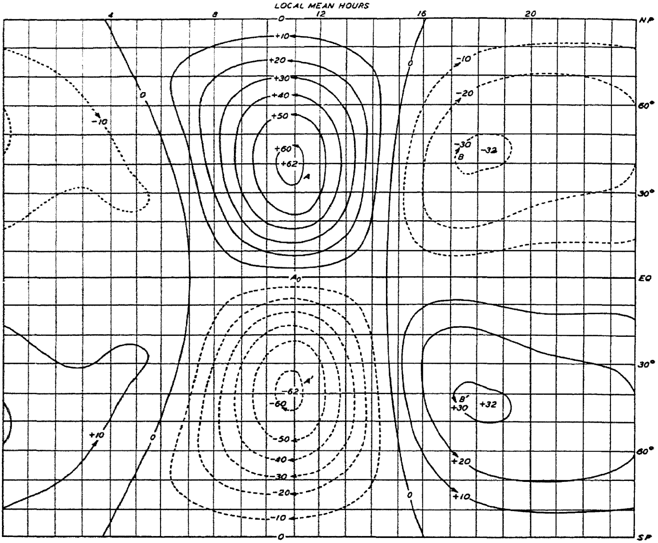


FIG. 11.—Isometrics of external current-functions in thousands of amp, all days, sunspot-minimum year 1902, from Chapman's analysis of magnetic diurnal variations at widely distributed observatories (*after Bartels*).

There is, however, a phase-difference between the empirical and calculated current-function harmonics, the latter culminating later at any given point than the former. In the above discussion self-inductance of the conducting layer was neglected as well as a possibility of phase-change of the pressure-wave with height which, both theory and observation indicate, tends to make the pressure-wave at great heights lag behind the pressure-wave at the Earth's surface. If these are taken into account, the phase-discrepancy becomes even greater, some estimates placing it at about 180°. However, the effect of a conducting Earth on the currents flowing in the high atmosphere is to accelerate the phase so that this apparent discrepancy between theoretical and observed phase should not be considered too seriously until all of the conditions have been properly taken into account.

By comparing the calculated and observed terms in the current-function, Chapman concluded that the maximum conductivity necessary to explain the variations was 25×10^{-6} EMU, being the product of the average specific conductivity and the thickness of the layer. This value does not seem irreconcilable with recent radio measurements of the ionic density.

The lunar diurnal variation is explained on the same basis by the Stewart-Schuster theory. In this case the lunar atmospheric tide instead of the solar tide gives rise to the velocity-potential from which the electromotive forces are derived. Although the tide-raising force of the Moon is twice as great as the tide-raising force of the Sun, the lunar atmospheric tide is only one-fifteenth as great as the solar atmospheric tide. The reason generally accepted for this difference is that the solar tide is partly of thermal origin coupled with phenomena of resonance. It is to be expected, therefore, that the lunar diurnal magnetic variation should be one-fifteenth as great as the solar diurnal magnetic variation.

The conductivity of the atmosphere, as previously explained, is a function of the Sun's zenith-angle and consequently bears a constant phase-relation to the velocity-potential of the solar tide. The phase-relation between the atmospheric conductivity and the lunar velocity-potential is not constant but varies continuously throughout each lunation. Thus the average lunar diurnal variation for an entire lunar month at the equinoxes should be that produced by the induced electromotive forces acting on an atmosphere of uniform conductivity with respect to longitude or local time, namely, a semidiurnal variation. The phase-shift of conductivity with respect to the lunar velocity-potential should give rise to other harmonics of continually changing phase. The phase-shift theoretically deduced for these harmonics agrees substantially with the phase-shift actually found as described in the preceding section.

Although numerous other theories have been advanced to account for the magnetic diurnal variation, only a few are worthy of consideration. Recognizing the fact that ions having thermal velocities of agitation in the region of long free-paths will spiral around lines of force in the presence of a magnetic field caused Gunn [311] to propose a diamagnetic theory of the solar diurnal variation.

An ion spiraling around the lines of magnetic force is essentially a magnetic shell, the magnetization of which is opposed to the impressed field. The intensity of magnetization is given by

$$J = -NkT/F$$

in which N is the number of free charges (of either sign), T is the absolute temperature, F is the intensity of the impressed magnetic field, and k is Boltzmann's constant.

In accordance with a well-known proposition of potential theory the magnetic potential of the diamagnetic layer may be regarded to a first approximation as the potential due to (1) a double layer of magnetic matter of density, $-kTNhZ/F^2$, plus (2) a distribution of magnetic pole over the layer of density

$$[1/aq][(1/\sin\theta)(\partial/\partial\theta)(kTNhX\sin\theta/F^2)+(1/\sin^2\theta)(\partial/\partial\lambda)(NkThY/F^2)]$$

in which h is the thickness of the layer and aq is its average radius, measured from the Earth's center, the other symbols being as previously defined. If the values of N, h, q, X, Y, Z, and F are everywhere known, the potential of the layer is uniquely defined. As N, principally, is a function of local time, the potential of the layer will also be a function of local time and gives rise to the solar diurnal variation. It is possible to represent such a potential as the sum of a series of spherical harmonics.

Considering only the first zonal harmonic of the Earth's permanent field so that the term containing λ and Y in the expression for the distribution of magnetic pole vanishes, and assuming a zenith-angle law for the distribution of N, Chapman [285] derived a series of spherical harmonics to represent the solar diurnal variations. The harmonics derived were in remarkably close formal agreement with those determined empirically. The value of T was taken as 300°K throughout the layer. The necessary value of Nh, the total number of ions in a column of the layer one cm^2 in cross-section, was found to be 5.2×10^{16} at the equator at noon, assuming the value at midnight to be sensibly zero. The extraordinarily great magnetic variations in the Western Hemisphere previously remarked upon would require an even greater value of Nh in that region. The necessary value seems considerably greater by several orders of magnitude than is indicated by the most recent results of radio investigations of the ionosphere.

Another possible cause for the solar diurnal variation has been discussed by Chapman [286]. Ions in a gravitational or electric field which is perpendicular to a magnetic field will describe a path the average direction of which is perpendicular to both. The nature of this motion may be comprehended from the following considerations: The ion, starting from a position of rest, moves in the direction of the electric or gravitational field. The velocity acquired by this ion causes it to be acted upon by a second force, at right-angles to its motion, due to the magnetic field, which, when the velocity becomes sufficient, causes the ion to move perpendicular to the electric or gravitational field and even against it until the kinetic energy acquired in its downward fall is expended against the electric or gravitational field. The ion now is again at the same equipotential surface which it originally occupied but is displaced along that surface some distance perpendicular to the magnetic field. This drift-velocity of the ion, assuming that collisions are few, is given by G/eF, in which G is the electric or gravitational force exerted on the ion, e its electric charge, and F is the magnetic field. If G is electric force, positive and negative ions drift in the same direction, and if equal numbers of positive ions and negative ions (or electrons) are present, except for second-order effects, no electric current results. If, however, G is gravitational, positive and negative ions move in opposite directions, giving rise to a drift-current.

An exact treatment of the drift-current theory has never been attempted. As has been previously inferred, the drift-current occurs only in that region of the ionosphere where the collision-frequency is low. Chapman supposes that the drift-current is a maximum at the equator at noon and gives rise to an accumulation of electrostatic charge, positive to the east and negative to the west of the noon meridian. Currents flowing in the lower region of the ionosphere where the collision-frequency is high would complete the circuit and give rise to such a system as is necessary to explain the diurnal variation. The estimated number of ions necessary to produce drift-currents sufficient to account for the diurnal variations is given as 2×10^{14} in a vertical column of the ionosphere one cm^2 in cross-section at the equator at noon, a value more in accord with the results of radio measurements than that required by the diamagnetic theory. However, no exact estimate of this required number is possible and the consideration of all requirements is more likely to increase the estimate than reduce it.

(6) COMPARISON OF THEORIES OF DIURNAL VARIATION

Of the three theories discussed, only one, that of Balfour Stewart, attempts to explain the lunar diurnal variation. No other theory has been proposed to explain the lunar effect. Neither the diamagnetic nor the drift-current theory could explain the lunar variation, as the Moon has no known ionizing effect on the upper region of the atmosphere such as they depend upon. The acceptance of either of these theories of the solar variation would require the acceptance of some other to explain the lunar variation.

The fact that the amplitude of the lunar variation varies almost exactly as the Moon's tide-raising force from apogee to perigee argues strongly that they are of tidal origin. Recognition must also be given the fact that the amplitude-ratio of the solar variation to the lunar variation is approximately the same as for the solar and lunar atmospheric tides.

Certain difficulties are encountered by the Stewart theory. One of these arises through the phase-differences of the actual variation and those predicted from the atmospheric tides. Although the electromotive forces as shown in Figure 10, computed from the air-motions at the Earth's surface, seem to be in proper phase, both theory and the meager observations available indicate that the air-motions at greater heights lag behind those at the Earth's surface, while the phase-lag of the current behind the electromotive force due to the inductance of the circuit makes the force of the variation-system appear at a given meridian still later. An advance of phase caused by the currents induced in the Earth, which has the effect of introducing capacitance into the primary circuit, to some extent diminishes this discrepancy. The drift-current and the diamagnetic theories also encounter difficulty in explaining the phase of the magnetic variation, since the center of the actual variation-system passes over a given meridian at about 11^h while the center should pass in the afternoon when the upper atmosphere probably attains its greatest total ionization. The results of radio observations, giving only the time of maximal density of ionization, so far fail to determine the time of greatest total ionization although, from numerous theoretical and empirical considerations, it does not seem possible that the greatest total ionization can occur before noon, particularly in the region of long free-paths, called the *F*-region, where such effects are probably of foremost importance.

Early estimates of the electric conductivity of the upper regions of the atmosphere failed to take account of the effect of the permanent magnetic field on this conductivity. Because of the spiraling of ions about the lines of magnetic force, the ionosphere is not an isotropic conductor, the direct-current conductivity in the regions of long free-paths parallel to the lines of magnetic force being much greater than perpendicular to them. The ratio of the perpendicular conductivity to the parallel conductivity is $\upsilon^2/(\upsilon^2 + \omega^2)$ in which υ is the collision-frequency and ω is the "spiraling" frequency, equal to eF/m where m is the mass of an ion, the other symbols being as previously defined. Thus, the large numbers of ions existing in the upper portions of the ionosphere where the collision-frequency is low can contribute little to the conductivity, so that the electric currents hypothesized by Balfour Stewart must be confined to the lower regions where the existence of adequate conductivity is questionable. However, radio investigations indicate that the ion-density of that region may considerably exceed the electron-density so that the total direct-current conductivity may be adequate.

Seeking information in the variation itself which would indicate the relative merits of the various theories, the anomalous variation recorded at the Huancayo and other magnetic observatories in the Western Hemisphere has been studied [316]. From the analysis previously referred to, a current-system was constructed which revealed that the maximum current-density occurred between the geographic equator and the Huancayo Magnetic Observatory, 12° south of the geographic equator, as shown in Figure 12. Electromotive forces calculated in accord with the Stewart theory for the same region, taking into account the southern displacement of the magnetic equator, are shown in Figure 13. Comparison with Figure 10 reveals that, while for the average conditions the equatorial current in the Stewart theory must flow against the induced electromotive forces, in the Western Hemisphere currents can pass around the entire circuit without encountering unfavorable electromotive forces. The circuit involving favorable electromotive forces entirely includes the region of most dense flow shown in Figure 12. Of course, reverse conditions exist in the opposite hemisphere but there they are not so pronounced.

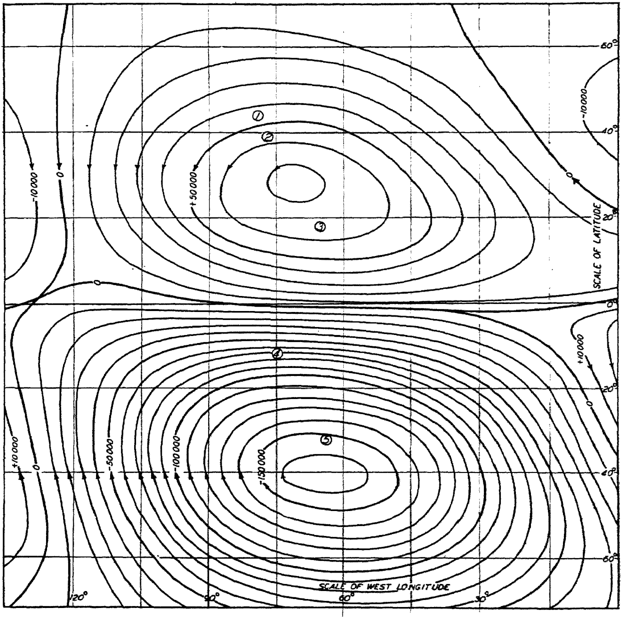


FIG. 12.—Isometrics of external current-function, Western Hemisphere, amp at 11^h, 75° west meridian mean time, international quiet days, equinox 1923 deduced from magnetic diurnal variations at Agincourt (1), Cheltenham (2), Vieques (3), Huancayo (4), and Pilar (5).

No means to account for the anomalous variation-system of the Western Hemisphere on the basis of the drift-current or diamagnetic theory suggests itself. There is no reason for supposing that the conditions of the upper atmosphere are notably different in the Western Hemisphere and, as the variation-system predicted by both theories is a rather simple function of the Earth's field, anomalies of severalfold seem inexplicable.

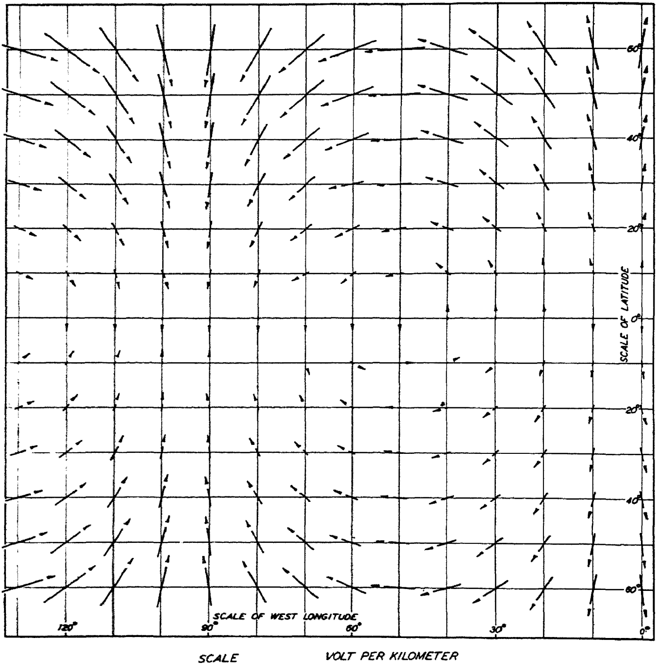


FIG. 13.—Electromotive forces in atmosphere of Western Hemisphere caused by semidiurnal atmospheric tides at 11^h, 75° west meridian mean time.

The change in character of the Huancayo Z-variation at the June solstice from a southern type in 1922 to a northern type in 1932, previously mentioned, indicates a fine structure in the variation-system of the Western Hemisphere such as can be explained on the basis of the Stewart theory but not, apparently, on the basis of either the drift-current or the diamagnetic theory.

Radio investigations have supplied some data for appraising the several theories. Several years of radio observations by the Carnegie Institution of Washington at the Huancayo (Peru) and Watheroo (Australia) observatories and by the National Bureau of Standards at Washington (United States), reveal that the maximal ion-density of the upper (F_2) region of the ionosphere experienced an annual rather than a seasonal variation during that time, the greatest maximal ion-density being observed near the December solstice in both hemispheres. If this may be taken as an indication of greatest total ionization of the upper region, and if the drift-current and diamagnetic effects occur principally in those regions (both of which views seem reasonable), then the amplitude of the solar diurnal variation should undergo an annual instead of a seasonal variation. The observed variation, quite definitely, is a function of the local seasons, being greatest in the Northern Hemisphere near the June solstice and in the Southern Hemisphere near the December solstice. This characteristic of the upper region of the ionosphere seems unfavorable to Chapman's suggestion that the currents causing the solar variation may flow in the lower regions of the ionosphere and those causing the lunar variation in the upper regions. Considerations of the necessarily low direct-current conductivity of the upper regions likewise argue against this suggestion. Occurrence of radio fade-outs due to dense ionization at low heights accompanied by enhancement of the diurnal variation, as described subsequently, shows that the diurnal variation is due to effects occurring in the lower part of the ionized region, and hence supports the dynamo-theory.

To epitomize—although no definite conclusions may be drawn at the present time relative to the correctness of any one theory—the evidence available is preponderantly in favor of the dynamo-theory of Balfour Stewart. Undoubtedly, both the drift-current effect and the diamagnetic effect may contribute in some measure to the observed magnetic variation, though slightly. On the other hand, the different effects may be complementary; for example, the dynamo-effect may account for the flow of currents in high latitudes while the drift-current effect may contribute largely to the flow in equatorial regions, with both dynamo-currents and drift-currents acting in conjunction in the equatorial regions of the Western Hemisphere.

VI. INDUCTION OF ELECTRIC CURRENTS WITHIN THE EARTH

All theories of the diurnal variation agree in ascribing the internal portion of the variation-field to currents induced within the Earth. The other transient variations, such as magnetic storms, likewise consist partly of effects from currents induced within the Earth by primary external causes. Much difference, or, rather, absence, of opinion exists relative to the origin of the internal changes known as secular variation, but the internal variations having periods of the order of a day, including the internal portion of diurnal-variation and magnetic-storm changes, are readily explained.

The theory of induction and decay of currents in a spherical conductor was first treated by Lamb [1268]. Further developments are due to Chapman, Whitehead, and Price [188, 864, 1277]. The expressed purposes of these investigations were to ascertain if the internal portions of the magnetic variations were ascribable to induced electric currents and to infer the magnetic and electric conditions of the Earth's interior from the relationship between the induced and inducing fields.

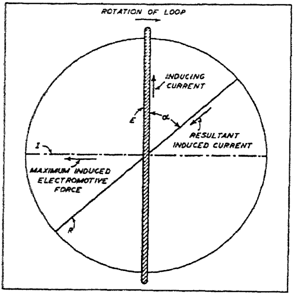

ROTATION OF LOOP
INDUCING CURRENT
E
α
RESULTANT INDUCED CURRENT
I
MAXIMUM INDUCED ELECTROMOTIVE FORCE
R

FIG. 14.—Induction of currents in sphere by rotating external circuit (E).

The physical picture of the induction of currents in a spherical conductor is a simple one. The induced currents, given roughly by Lenz's Law, tend to prevent the vertical component of the flux of the inducing field from entering the sphere. The phase-relationship for a magnetic field rotating about the sphere is evident from Figure 14. If an electric current flows through the loop, E, rotating about the sphere in a clockwise course, the maximum electromotive force in the sphere will be along the meridian, I, perpendicular to E. If the sphere is a very poor conductor, the electromotive force and the current produced in the sphere by it will be approximately in phase, so that the induced and inducing currents will have a phase-difference of nearly 90°. The induced current in this case is governed largely by the resistance of the sphere. If the sphere is a very good conductor, the current will lag behind the electromotive force by nearly 90° so that the current along I will attain its maximum at the time that E has become almost parallel to I. The induced current in this case is governed largely by the inductance of the sphere. The induced current will be oppositely directed to the inducing current but, with reference to the magnetic effects they produce, the induced and inducing currents will be in phase. For intermediate values of conductivity the maximum induced current will be along the circle, R, which makes an angle, α, with the circle, E. The values of the conductivity which cause a given value of α are dependent on the size of the sphere and rapidity of the rotation. For the case just cited the induced current is in *advance* of the inducing current, as has been found for the magnetic diurnal variations. The intensity of the internal current will also be affected by the conductivity.

If the circuit, E, is considerably larger than the sphere, points may be located above the surface of the sphere but inside the circuit, E, at which the ratios of the magnetic fields due to the inducing current and the induced current will have various values, the phase of the two remaining the same.

The mathematical treatment of the problem is more complicated. The magnetic variations are derivable from a vector-potential, $\vec{V}$, defined by $\vec{F} = \text{curl } \vec{V}$, it being assumed that the permeability of the conducting sphere and of the space about it is unity. The components of the vector-potential of the external and internal portions of the variations in non-conducting space are of the form

$$\begin{array}{lll}
V_r = 0 & V_r = 0 & \text{(radial)}\\
V_\theta = -[1/(n+1)][(\partial/\sin\theta\partial\lambda)W_{nE}] & V_\theta = [1/n][(\partial/\sin\theta\partial\lambda)W_{nI}] & \\
 & & \text{(northward)}\\
V_\lambda = [1/(n+1)][(\partial/\partial\theta)W_{nE}] & V_\lambda = -[1/n][(\partial/\partial\theta)W_{nI}] & \\
 & & \text{(eastward)}
\end{array}$$

respectively, W_{nE} and W_{nI} being the magnetic scalar potentials of external and internal origin given by the spherical harmonics of degree n. The further relationships hold for conducting media

$$\vec{E} = -(1/c)(d/dt)\vec{V}$$

and

$$\nabla^2\vec{V} = [4\pi k/c^2][(d/dt)\vec{V}]$$

in which k is the conductivity of the medium, c is the velocity of light, and $\vec{E}$ is the electric force. In case $k = 0$

$$\nabla^2\vec{V} = 0$$

In space occupied by conducting matter the components of $\vec{V}$ are the corresponding derivatives of functions u which satisfy the equations of condition. These u-functions are products of spherical harmonics and certain R-functions which involve the radius of the conducting sphere, its conductivity, and the time-factor of the inducing harmonic. Since the tangential and normal magnetic intensities must be continuous at the surface of the conducting sphere, they may be correspondingly equated and theoretical ratios derived for the external inducing field and the internal induced field. These ratios are expressed in terms of the R-functions

$$I_n/E_n = [n/(n+1)]q^{2n+1}[1 - R_n/R_{n-1}]$$

the ratio I_n/E_n being what would be observed at the surface of a sphere of given radius $(1/q)$ times as great as the radius of the conducting sphere, n referring to the degree of the harmonic and the R-function. If the harmonics of the magnetic potential vary periodically, the ratio I_n/E_n is a complex number and obviously the second bracketed expression in the above equation is also a complex number, the imaginary portion involving the phase-difference of the internal and external harmonics. In the diurnal variations of terrestrial magnetism the harmonics are periodic and the ratio I_n/E_n is imaginary.

When $q = 1$, that is, when I_n/E_n is observed at the surface of the conducting sphere, both the ratio of the absolute values of I_n and E_n and their phase-difference are uniquely determined for given values of the radius and conductivity of the conducting sphere and the degree and frequency of the harmonics. Conversely, if a certain relative amplitude and phase-difference of I_n and E_n are observed, only one value of conductivity can be inferred for each harmonic, assuming that the entire Earth is uniformly conducting. The values of conductivity for the Earth inferred separately for each harmonic of the diurnal variation do not agree if this assumption is made. However, if q is assumed to be unknown, that is, if the conducting sphere is smaller than the Earth, the relative amplitudes and phase-differences observed for two harmonics can be used to infer both the radius and the conductivity of the conducting sphere. Both the phase-differences and amplitude-ratios of the individual internal and external harmonics can be brought into satisfactory theoretical agreement on the hypothesis that the currents giving the internal portion of the diurnal variations flow in a spherical core separated from the surface of the Earth by a non-conducting layer 250 km thick. The conductivity required for this core is 3.7×10^{-13} EMU. This value may be compared with 4×10^{-11} EMU for sea water, 10^{-16} EMU for ordinary rock, and 6.1×10^{-4} EMU for copper.

The conductivity deduced for the core does not necessarily apply at the center of the Earth. Owing to the comparatively high frequency of the harmonics of the diurnal variation as compared with the inductance of the Earth—the inductance is proportional to the square of the radius—the central portion of the core is efficiently screened from the magnetic effects of the diurnal variation. To infer a conductivity for the central portion of the core, extremely long-period variations would have to be observed.

Consideration of the aperiodic variations, observed during magnetic storms, by Chapman and Price, indicated a conductivity for the core of 44×10^{-13} EMU, 12 times as great as indicated by the diurnal variations. These two conductivities may be reconciled by assuming that the conductivity of the core increases with increasing depth. The slower changes occurring during magnetic storms induce currents in the deeper regions where higher conductivity exists [see also 408-A].

From the ratios of the induced and inducing fields at various stages of the aperiodic fluctuations it should be possible to infer the permeability of the core. Permeability greater than unity would cause a reversal in sign of the internal harmonics after the induced currents have had time to die away. Attempts to determine the permeability have been inconclusive, but the indications are that it does not sensibly differ from unity.

Another effect which must be taken into account involves the high conductivity of the large oceanic areas. Owing to the highly complicated shapes of oceanic basins, the problem presents insurmountable difficulties to mathematical treatment. Very shallow seas and layers of moist earth would have an inappreciable effect, even though they covered the entire Earth, but if deep oceans covered the Earth, the interior would be efficiently screened from the external magnetic field. Comparison of the magnetic observations at mid-continental and mid-oceanic stations indicates, qualitatively, that the oceans play an important part in affecting the induced currents.

VII. MAGNETIC DISTURBANCES

Besides the ordinary diurnal variations of the Earth's magnetism, other transient variations occur which, by analogy with disturbed meteorological conditions, are called magnetic storms. During these storms extraordinarily large variations in the magnetic elements occur. Ranges sometimes exceed 1,000 γ in low and middle latitudes, while still greater fluctuations take place in polar regions. Contrasted with this, the ranges on quiet days in low and middle latitudes are never known to exceed 100 γ except in the region around Huancayo.

Magnetic storms possess many distinctive features. Major storms affect all portions of the Earth simultaneously and the effects of even minor storms are evidenced over wide regions. Although the type of variation on a quiet day may be predicted with a considerable degree of certainty, the changes during a magnetic storm defy prognostication. In common with the ordinary diurnal variations, magnetic storms have their primary origin in regions above the Earth's surface [188].

Despite their erratic nature, certain systematic characteristics of magnetic storms have been discovered. Magnetic storms tend to occur at intervals of about 27 days, to vary in frequency with the number of spots upon the Sun, and to be more numerous at the times of the equinoxes, tendencies which are fully treated in Chapter VIII of this volume. Magnetic storms exhibit certain general features in their effects on the Earth's magnetic field.

Most major magnetic storms are characterized by a sudden beginning which is simultaneous at all places on the Earth to within the accuracy of the observations. The typical form of the variation at various latitudes during moderate magnetic storms is shown in Figure 15. This representation, due to Chapman, was obtained by averaging, at hourly intervals, the departures from the pre-storm value at various observatories for 40 moderate storms using time of beginning of the storms as the time-origin. Magnetic storms vary in duration—shorter ones lasting only for several hours while others continue for several days—so that such an averaging process necessarily conceals important details. However, examination of the individual storms portrayed in Figure 16 shows that these average departures may be regarded as typical.

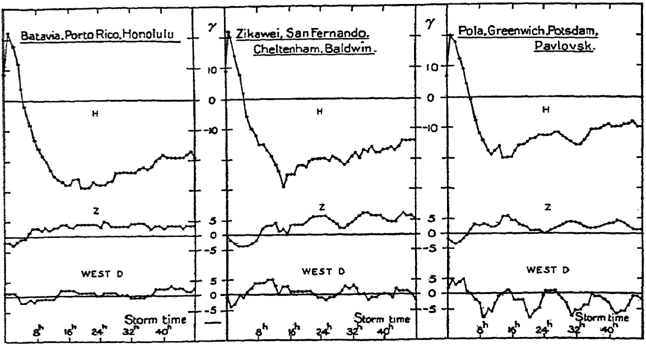


FIG. 15.—Average variation in horizontal intensity, vertical intensity, and declination, for various latitude-belts, during magnetic storms, for time in hours after beginning of storm (*after Chapman*).

(1) STORM-TIME VARIATIONS

The average course of magnetic storms in middle latitudes, plotted according to "storm-time," is independent of the longitude of the observing station. The course of the changes in declination is rather erratic while in horizontal intensity and vertical intensity it is quite characteristic.

Horizontal intensity first increases and remains above its pre-storm value for several hours. This has been called by Chapman the positive phase of the storm. Often this increase occurs during the first few minutes of the storm in the form of an extremely rapid rise, called a "sudden commencement." A few hours later the horizontal intensity decreases, the negative phase of the storm falling toward a minimum which is attained, on the average, about two-thirds of a day after the beginning of the storm. Recovery of the element occurs more or less exponentially at first, although after a couple of days recovery seems to be nearly linear and to

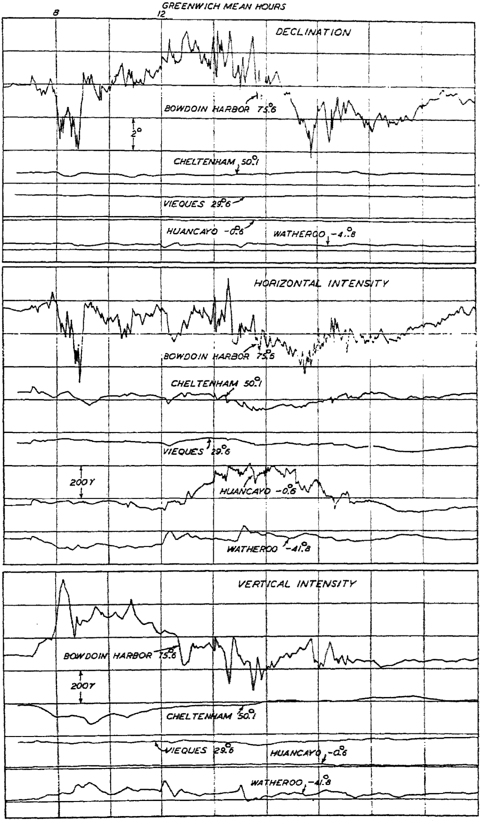


FIG. 16.—Variations in declination, horizontal intensity, and vertical intensity during magnetic storm on March 14, 1922, at various geomagnetic latitudes (Φ).

continue so until the next magnetic disturbance occurs. These changes in horizontal intensity are of greatest magnitude near the geomagnetic equator; they decrease with increasing latitude but again become great and take on a different character as extremely high latitudes are approached. The negative phase, sometimes called the main phase, almost always lasts longest and includes the greatest and most erratic changes.

The course of the storm-time variations in vertical intensity is opposite to that in horizontal intensity, of less magnitude, and more erratic. Close to the geomagnetic equator the average variation is substantially *nil* but in middle latitudes, north or south of the geomagnetic equator, vertical intensity is below the pre-storm value, in a *numerical* sense, during the positive phase of the storm. Corresponding to the decrease in horizontal intensity, vertical intensity rises above the pre-storm value, numerically, during the negative phase of the storm. The return to the pre-storm value is less clearly marked.

The average course of the variations in low and middle latitudes during magnetic storms is such as would be produced by an electric current flowing around the Earth in a ring several Earth's radii in diameter, coplanar with the geomagnetic equator. During the positive phase this hypothetical current flows from west to east, but during the negative phase of the storm the current flows from east to west, gradually dying out. Accompanying these external currents, corresponding currents are induced in the Earth which diminish the magnetic flux entering the Earth. The magnetic effect of these induced currents augments the horizontal components of the storm-field and decreases the vertical components. These systems of currents would cause the compass to point more nearly toward the geomagnetic pole—which is precisely what is observed. At observatories where the compass does not ordinarily point toward the geomagnetic pole, this effect is most pronounced.

An equally comprehensive picture of the course of storm-time variations in high latitudes is not possible owing to the greater complexity of the phenomena there and to the scarcity of data from polar regions. Figure 15 clearly indicates that the magnetic departures during the negative phase of the storm are fairly represented by the average value of the magnetic elements during the storm-days as compared with the values on quiet days. The vector-difference of the average magnetic field on the 60 "stormiest" days of 1927 as compared with the 60 least stormy days for the same year at various observatories is represented in Figure 17. The horizontal components are directed southward and tend to be aligned with the geomagnetic meridians even though those directions are not the compass-directions at all the observatories. The greatest magnitude of the horizontal components appears near the geomagnetic equator, decreases with increasing latitude north and south, and then increases again to a second maximum in a region about 20° from the geomagnetic poles known as the auroral zones.

The distribution of the vertical component of the vector-difference is more striking. Vertical intensity is unaltered near the geomagnetic equator, increased, in a numerical sense, in middle and polar latitudes, but decreased in a numerical sense close to the auroral zones.

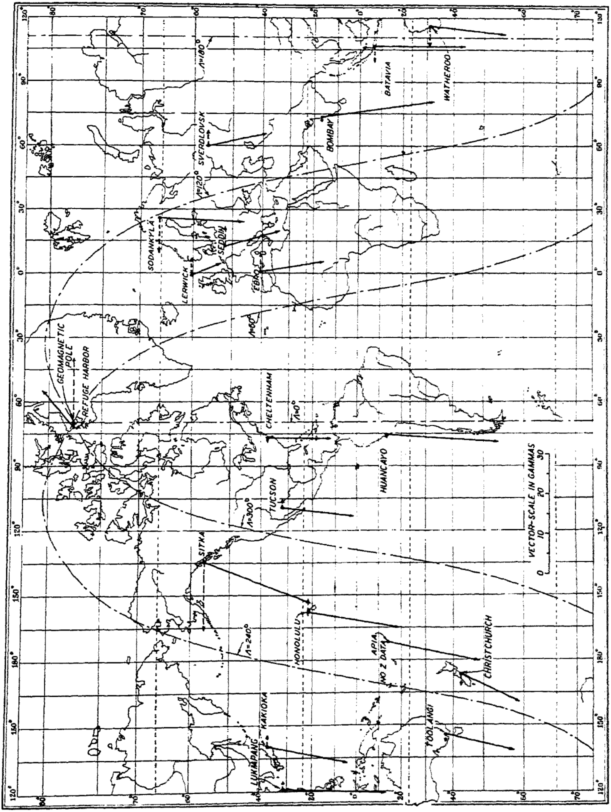


FIG. 17.—Mean vector-differences magnetic intensity for disturbed minus quiet days, 1927; —— = horizontal intensity; - - - = vertical intensity.

Harmonic analysis of the vectors shown in Figure 17 [437] discloses that the effect is due principally to causes above the Earth's surface, although a considerable portion is of internal origin. These storm-time changes are nearly completely representable by zonal harmonics using the geomagnetic pole as the pole of the coordinate system, the harmonics employed being naturally of odd degree because of the asymmetry of the storm-potential north and south of the geomagnetic equator. The ratio of the internal to the external portions of the harmonic, P_1, was found to be 0.39, in close agreement with the ratio of the internal to external harmonics obtained for the solar and lunar diurnal variations. The ratios for the harmonics, P_3 and P_7, are quite anomalous which may signify that the process of induction during magnetic storms is very complicated.

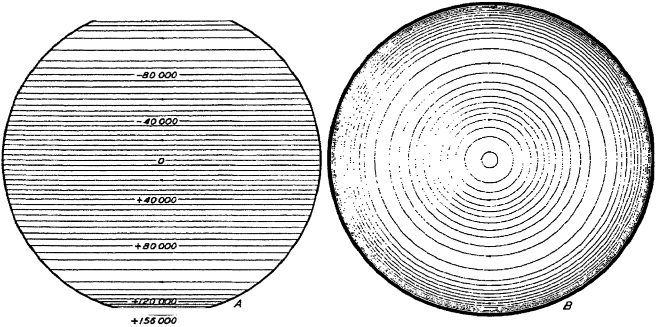


FIG. 18.—Isometrics of equivalent current-function in amp in spherical shell 100 km above Earth's surface for magnetic storms, disturbed minus quiet-day differences, 1927; (*A*) view from geomagnetic equator, (*B*) view from north geomagnetic pole.

The current-system flowing in a layer 100 km above the Earth's surface necessary to cause the portion of the average storm-field of external origin is shown in Figure 18. This current-system was constructed from the coefficients of the harmonics of the storm-field obtained by the above-mentioned analysis. The maximal density of current-flow occurs in the equatorial region and in the auroral zones. The total current encircling the Earth to produce the storm-field in the external system exceeds 300,000 amp, while a current over half this strength flows in the internal system. This figure, however, applies only to the mean storm-field for the 60 stormiest days of 1927; during the most intense phase of the strongest storms it is probably exceeded by nearly two orders of magnitude [386].

The current-configuration shown in Figure 18 is not the only one which would produce the observed effects. If the current is known to flow within a definite, reasonably thin layer of the outer atmosphere, its configuration is uniquely defined by the magnetic effects. But so long as the regions in which the currents flow (if the effects are due to currents) are unknown, an infinite number of configurations are possible, in accord with principles of potential theory. For example, much of the current may be confined to a toroid, coplanar with the geomagnetic equator, the radius of which is several times that of the Earth, while the remaining portion of the current may flow in the outer atmosphere. However, to produce a magnetic field of a given configuration, the current-system must have a corresponding configuration. Irregularities in the configuration of the magnetic field require corresponding irregularities in the current-system, and the required intensity of these irregularities increases with the distance of the currents from the magnetic effects which they produce. Thus, while maxima and minima in the magnetic effects may be produced by similar maxima and minima in a current-system close to the Earth's surface, a current-system at a great distance from the Earth could produce the same effect only if the direction of flow is reversed in various zones, flowing eastward in some and westward in others. For this reason it seems most plausible to assign the currents to regions quite close to the Earth.

(2) Diurnal variation on disturbed days

Another aspect of magnetic storms is revealed by the diurnal variation of the magnetic elements on days which are notable for their storminess. While the storm-time variation progresses roughly according to universal time, a characteristic variation is superimposed upon it which progresses according to the local time at each observatory. This variation is quite distinct from the ordinary diurnal variation.

The form of this diurnal variation on disturbed days at various latitudes compared with the typical quiet-day variation observed at the same stations, is shown in Figures 19. The distinctive features of the horizontal-intensity variation are a forenoon maximum and afternoon minimum in low latitudes with a complete inversion of this form in high latitudes. The transition takes place at about 55° for the disturbed diurnal variation, while for the quiet diurnal variation the transition occurs slightly below 40°.

The vertical-intensity variation exhibits forenoon minima and afternoon maxima at all stations south of the auroral zone, the amplitude being slight in low latitudes and considerable in high latitudes. Contrasted with this condition, the quiet-day variation in vertical intensity has its greatest amplitude in middle latitudes—the transition-region for the quiet-day variation in horizontal intensity. In high latitudes the variation in vertical intensity on quiet days closely resembles that on disturbed days, though the amplitude is not so great. This fact is taken to indicate that even on quiet days some vestige of disturbed-day phenomena is present in polar regions.

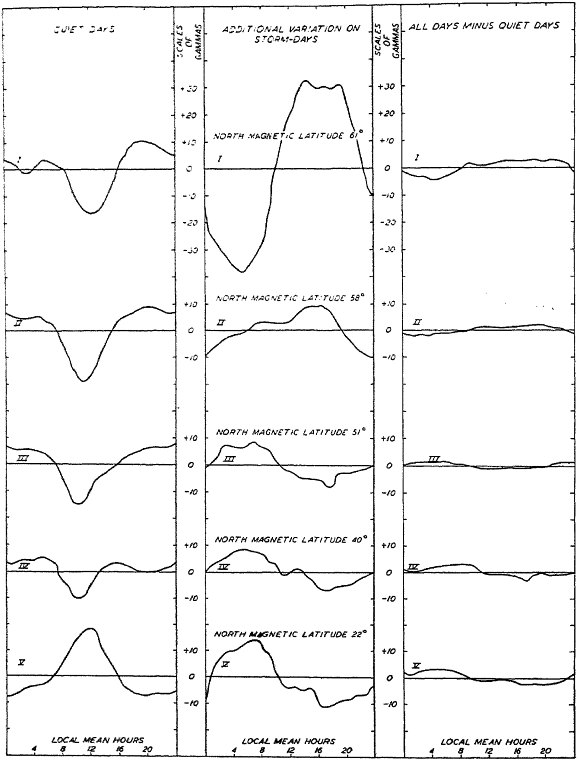


FIG. 19-A.—Average diurnal variation in horizontal intensity for various latitudes in Northern Hemisphere (*after Chapman*).

The variation in east declination shows a broad midday minimum. The ranges increase with increasing latitude for both the disturbed-day and quiet-day variations.

South of the equator the disturbed-day variations in declination and in vertical intensity are inverted while the variation in horizontal intensity is symmetrical with respect to the equator—another point of resemblance between the two systems. For days of moderate storminess the magnitude of the disturbed variation is approximately the same as the ordinary quiet-day variation.

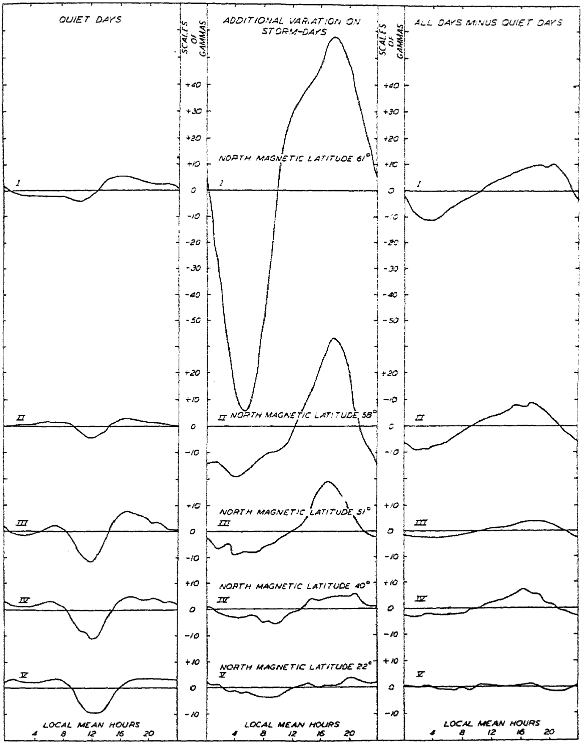


FIG. 19-B.—Average diurnal variation in vertical intensity for various latitudes in Northern Hemisphere (*after Chapman*).

The significance of the mean diurnal variation on disturbed days must be given special consideration. Occasionally some days occur during which the course of the magnetic variation is exceptionally smooth at all

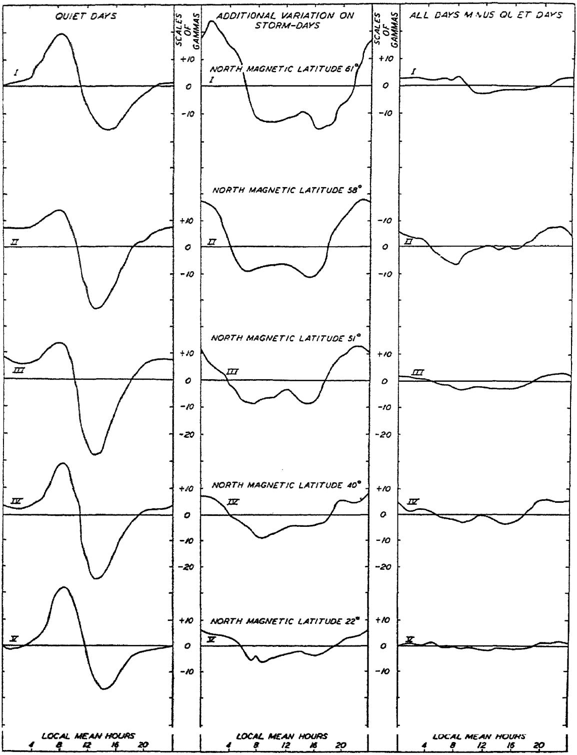


FIG. 19-*C*.—Average diurnal variation in east declination for various latitudes in Northern Hemisphere (*after Chapman*).

observatories. The variation on such a day is nearly identical with the course obtained by taking the mean for a large number of fairly quiet days. Thus the mean variation on quiet days may be considered as representative of a "normal" or an idealized quiet day from which all vestige of the effects of magnetic disturbance has been removed. But this is not true for magnetic storms.

It is questionable if any individual storm closely approximates the composite of many magnetic storms. Many individual storms exhibit quite clearly the form of the storm-time variations, but the diurnal variation or local-time component is not individually evident. To use an analogy: The wind-velocity on days of thunder-storm might be averaged and disclose that the peculiarity of such days is a wind from the west between the hours of two and five with a maximum velocity of ten miles per hour. The fact that the wind came in gusts with velocities of 60 or 70 miles per hour, exhibited sudden shifts of direction, and persisted for only a few minutes would be completely concealed by this averaging.

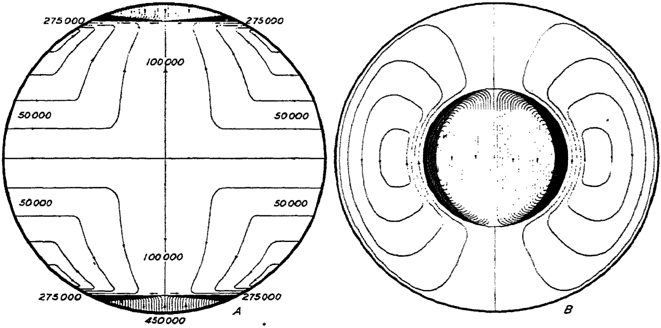


FIG. 20.—Idealized current-system in amp to produce additional diurnal variation on magnetically disturbed days, magnetic and geographic axes being assumed coincident; (*A*) view from equator at noon meridian, (*B*) view from north pole (*after Chapman*).

Since erratic fluctuations are distinguishing features of magnetic storms, it is possible that the characteristic diurnal variation on disturbed days may be a purely fictitious representation of sporadic fluctuations which have a tendency to occur in one direction during certain portions of the day and in another direction during other portions. These erratic fluctuations will be given further consideration subsequently.

Spherical harmonic analysis of the diurnal variation on disturbed days has never been attempted, and, in view of the possibilities mentioned in the preceding paragraph, conclusions which may be drawn from such an analysis are questionable. By means of certain assumptions relative to the portion of the disturbed-day diurnal variation due to causes inside and outside the Earth, Chapman has constructed a current-system which would give rise to these variations, shown in Figure 20. Figure 18, showing the current-system for the storm-time variations, is not comparable numerically with Figure 20 as it is based on different data, it being necessary to multiply the intensities of the storm-time system portrayed in Figure 18 by about two and one-half to effect the necessary reduction. The composite of the current-system to give both the storm-time variation and disturbed local-time or diurnal variation is shown in Figure 21, as derived by Chapman on the basis of the previously mentioned assumptions.

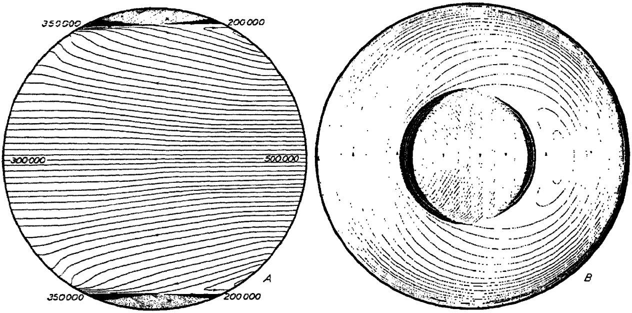


FIG. 21.—Idealized current-system in amp to produce magnetic storms, magnetic and geographic axes being assumed coincident; (*A*) view from equator at noon meridian, (*B*) view from north pole (*after Chapman*).

(3) MAGNETIC BAYS

The most distinctive feature of magnetic disturbance is an irregular course in the variation of the magnetic elements. On a quiet day the variation in any element may be almost completely represented by three or four sine-waves having wave-lengths of one, one-half, one-third, and one-fourth day and suitable phase-angles. An equally good representation of the variation on a disturbed day would require the use of a ridiculously large number of sine-wave components.

This erratic character of the magnetic variations on disturbed days is due to the superimposition of various types of fluctuations on the general trend of the variations. These fluctuations usually give rise to the extreme magnitudes of the magnetic elements on disturbed days. The maxima and minima not infrequently occur within an hour of each other—indicative of the irregularity and rapidity of the field-changes during magnetic storms.

During magnetic storms the magnetic elements sometimes increase or decrease quite rapidly, attain maximal departures, and then return to their previous values—the entire event occurring within an hour or two. On the photographic magnetic records these changes resemble indentations in a coast-line, for which reason the term "bays" has been usually applied to them. Usually many of these bays occur during a single storm, some of great magnitude and some quite small, and often one is superimposed partly or entirely upon another. The disentanglement of individual bays during a large magnetic storm is difficult. However, the occasional appearance of bays on days which are otherwise free from disturbance has supplied an opportunity for detailed study of these phenomena and for drawing certain generalizations.

In middle latitudes "positive" bays—involving increases in horizontal intensity—tend to occur most frequently around local midnight, while "negative" bays occur most frequently around local noon [443, 448]. Positive bays are ordinarily of greater magnitude than negative ones. When the changes in all the elements are considered, a bay is representable at a given observatory by the motion of the total magnetic vector so that its end describes a closed loop confined approximately to a plane. The tilt and direction of the bight relative to the end-points is determined largely by the latitude of the observatory and the time of occurrence of the bay.

Knowledge of the geographical distribution of bays [415] contributes to an understanding of their nature. A large bay is manifested almost simultaneously all over the Earth, its form and magnitude being governed by time and geographic position. In equatorial regions bays are comparatively inconspicuous, but in high latitudes—near the auroral zones—their magnitudes are about ten times as great as in middle latitudes. Also they are less simple in form near the auroral zones, being of a more jagged character. Positive bays in middle latitudes seem to be accompanied, along the same meridian, by negative bays near the auroral zones.

Studying the various aspects of magnetic phenomena in polar regions, Birkeland [66] isolated a type of disturbance enduring for an hour or two to which he assigned the name polar elementary storm. These storms are accompanied by bays in lower latitudes. A comprehensive view discloses that bays and polar elementary storms are simply different aspects of the same phenomenon, as he has shown in his great memoir.

Data obtained from the combined efforts of many nations and many institutions during the Second International Polar Year, 1932–33, have contributed to a better understanding of these phenomena.

In Figure 22 are shown the currents flowing in the upper atmosphere necessary to produce the changes in horizontal intensity occurring in a bay. That they are due primarily to external causes with which are associated currents induced within the Earth is readily concluded from simple physical reasoning. The currents in Figure 22 are constructed on the assumption that the bays are due entirely to external currents, an admittedly incorrect assumption, but one which leads toward an understanding of their origin.

Considering only the field-changes recorded near the auroral zone, which are about ten times as great as those occurring in middle latitudes, bays may frequently be resolved into a very simple form. Roughly, the changes in horizontal intensity and in vertical intensity near the auroral zone may be attributed to a flow of current along a narrow and lengthy path in the upper atmosphere roughly parallel to the auroral zone. Figure 23 shows the field-changes recorded at several stations near the same meridian during a bay-disturbance.

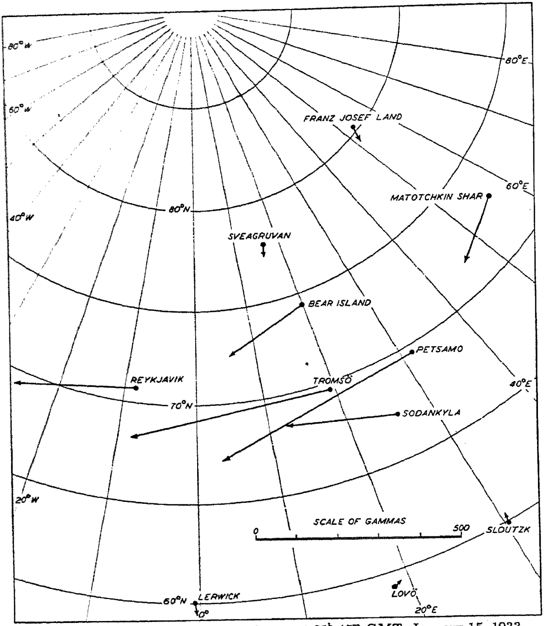


FIG. 22.—Current-arrows for disturbance at 21^h 45^m GMT, January 15, 1933.

This characteristic distribution of magnetic disturbance was first discussed by Birkeland. The disturbance may be regarded as the field due to current-flow in a long narrow region of the ionosphere. Proceeding on this assumption, Birkeland calculated the heights and strengths of the currents flowing along the auroral zone for various bays. Strengths of the currents were of the order of 1,000,000 amp, and the heights varied from slightly over 100 km to several hundred km.

In calculating these values Birkeland neglected the effect of currents induced in the Earth by the primary external currents. Chapman [386] has called attention to inaccuracies so introduced. Determination of heights of the currents causing a bay-disturbance by this method is shown in Figure 24. Data used in this determination are from Figure 23.

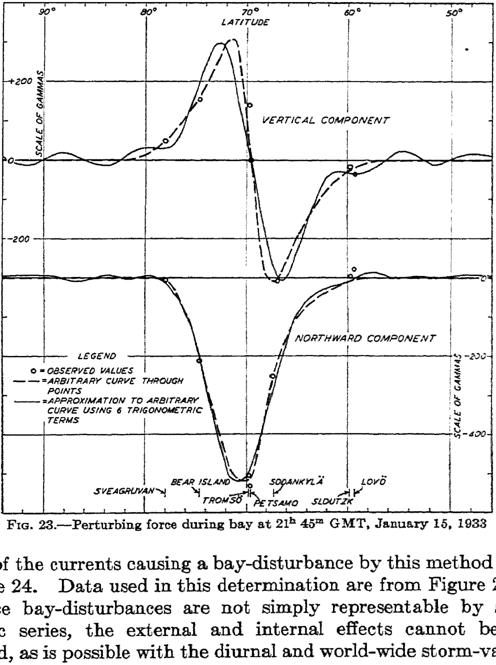


FIG. 23.—Perturbing force during bay at $21^h\ 45^m$ GMT, January 15, 1933

Since bay-disturbances are not simply representable by spherical harmonic series, the external and internal effects cannot be readily separated, as is possible with the diurnal and world-wide storm-variations. However, some success may be achieved by resorting to less elegant methods [1271]. In this method curvature of the Earth is neglected and the current is assumed to be of infinite extent along its direction of flow. Thus the problem becomes one in two-dimensional potential-theory in the plane perpendicular to the Earth's surface and to the direction of the current. The magnetic forces are derivable from a potential at all points along the line formed by the intersection of this plane with the Earth's surface. This potential arises from two sources, one a current-sheet above the Earth's surface and the other a current-sheet beneath the Earth's surface. The equation

$$\partial^2 W/\partial x^2 + \partial^2 W/\partial z^2 = 0$$

must be satisfied subject to the condition that the internal contribution vanishes at $z = +\infty$ and the external contribution vanishes at $z = -\infty$, z being measured vertically upward.

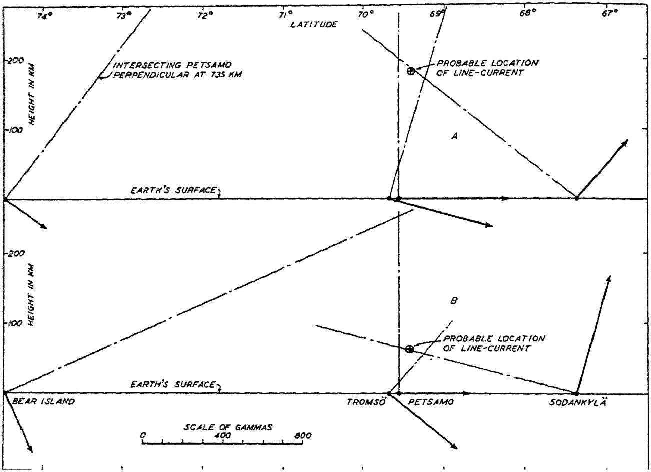


FIG. 24.—Determination of heights of auroral-zone currents by projection, (*A*) internal field being neglected, (*B*) internal field being assumed half as great as external.

$$-W = A_0 x + \sum_1^n [e^{+nz}(A_{en} \cos nx + B_{en} \sin nx) + e^{-nz}(A_{in} \cos nx + B_{in} \sin nx)]$$

satisfies these conditions, W being expressed with reference to the potential at some point, which for convenience is taken on the axis-line a great distance from the center of disturbance. The components of magnetic intensity at the Earth's surface (when $z = 0$) due to this potential are

$$X = -\partial W/\partial x = A_0 + \sum_1^n [-n(A_{en} + A_{in}) \sin nx + n(B_{en} + B_{in}) \cos nx]$$

$$Z = -\partial W/\partial z = \sum_1^n [n(A_{en} - A_{in}) \cos nx + n(B_{en} - B_{in}) \sin nx]$$

Observed values of X and Z at the Earth's surface may be developed in trigonometric series of the form

$$X = a_{0x} + \sum_1^n [a_{nx} \sin nx + b_{nx} \cos nx]$$

$$Z = \sum_1^n [a_{nz} \cos nx + b_{nz} \sin nx]$$

The a's and b's so obtained are identified with the corresponding terms in the derivatives of the potential. Thus, except for the term involving A_0, the field may be separated into internal and external contributions, since the coefficients of the series in X contain the sums of the internal and external parameters while the coefficients of the series in Z contain their differences. A_0 is arbitrarily separated into internal and external portions proportional to the average amplitudes of the internal and external periodic terms.

The series expressing the portion of X at the Earth's surface due to external causes is identical, except for a factor of proportionality, with the current-density in a thin sheet at an infinitesimal height which would give rise to it. The external portion of X may be evaluated at various heights, provided these heights do not exceed the actual height of current-flow. This evaluation of X at various heights gives the distribution of current-density in a thin sheet assumed to flow at those heights which would produce the magnetic field observed at the Earth's surface.

Computations conducted according to this method using the data of Figure 23 are shown in Figure 25. At a height of 200 km the equivalent current-distribution is as complicated as the trigonometric representation, using the same number of terms, of a line-current—the simplest reasonable assumption. But the ratio of the higher harmonics to the first harmonic in the representation of a line-current is unity. This does not appear to be true for the case in question from which it is concluded that the current producing the disturbance studied has appreciable width. The height of the current is taken to be not over 100 or 150 km since at these heights the negative portion, representing current-flow in the opposite direction, becomes considerable.

(4) SUDDEN COMMENCEMENTS

The sudden commencement of the great magnetic storm of May, 1921, as recorded at several observatories, is illustrated in Figure 26. Such sudden commencements are simultaneous—to within a few seconds—at all places on the Earth where they are recorded. They vary in magnitude from a few γ to well over 100 γ, this entire change occurring within from one to ten minutes.

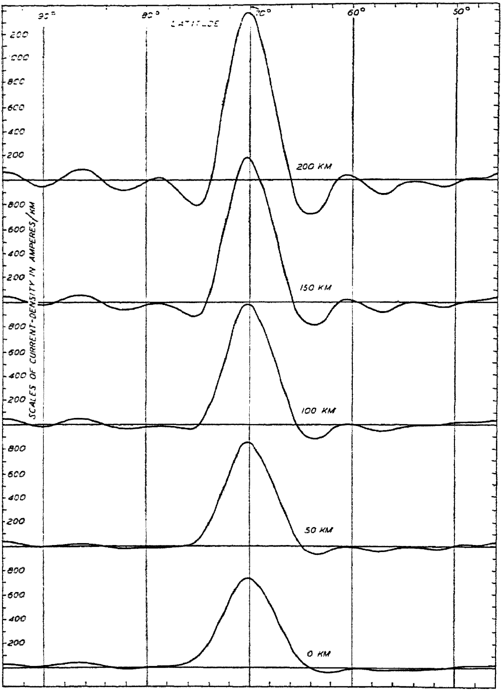


FIG. 25.—**Equivalent westward current-sheet at various assumed heights causing bay at 21^h 45^m GMT, January 15, 1933.**

Sometimes the characteristic increase in horizontal intensity is preceded by a smaller decrease of very short duration, as illustrated in the record for Potsdam. The records for Sitka, Agincourt, and Cheltenham show that a storm may begin with an equally abrupt decrease in horizontal intensity although a characteristic sudden commencement may have been recorded at most other observatories. Initial decreases of this nature are usually recorded at places which are slightly west of the noon meridian when the storm begins. Such initial decreases are not nearly so uniform in character, so great in magnitude, or so abrupt as the increases. Thus an increase in horizontal intensity may be regarded as the significant feature of a sudden commencement. Concomitant changes in vertical intensity and declination are not nearly so well defined.

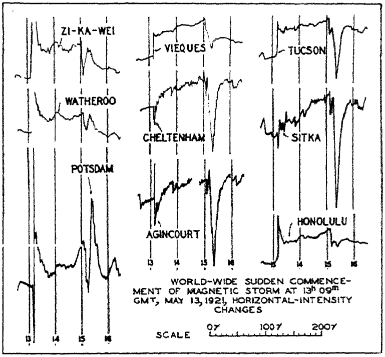


FIG. 26.—World-wide sudden commencement of magnetic storm at $13^h\ 09^m$ GMT, May 13, 1921 horizontal-intensity changes.

Often sudden-commencement movements are observed which are followed by increases in activity too mild to be classed as storms. Investigation of all types of sudden commencements at the Ebro Observatory (40°8 north latitude and 0°5 east longitude) by Rodés [430] and at the Watheroo Observatory (30°3 south latitude and 115°9 east longitude) by McNish [413] reveals that sudden commencements are more frequent during the local summer and during the afternoon (local time) at both stations, although these stations are in opposite hemispheres and differ in local time by nearly eight hours. On the other hand, the relative frequency of sudden commencements in various years is nearly the same at both observatories—closely paralleling the sunspot-numbers and measures of world-wide magnetic activity.

These time-distributions of sudden commencements clearly indicate that they are governed by two factors—one, of extra-terrestrial nature, probably associated with solar conditions, and one dependent upon the position of the observatory with respect to latitude and local time. Pronounced sudden commencements are recorded all over the world, but weaker ones appear only if the observatory is propitiously situated relative to the Sun at the time the primary cause reaches the Earth.

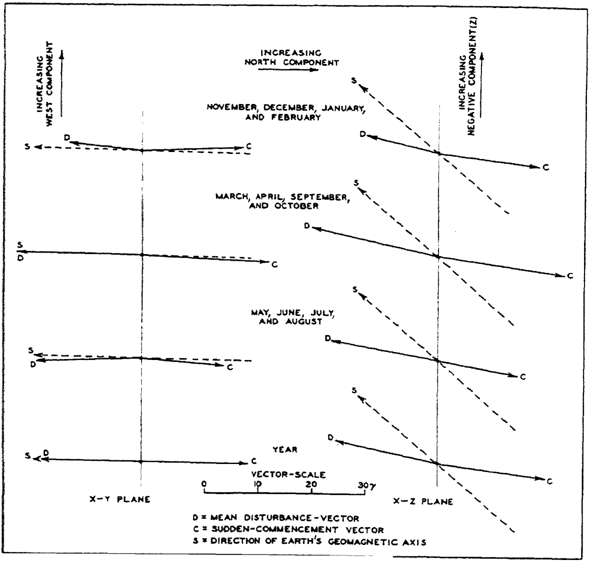

INCREASING WEST COMPONENT
INCREASING NORTH COMPONENT
INCREASING NEGATIVE COMPONENT(Z)
NOVEMBER, DECEMBER, JANUARY, AND FEBRUARY
MARCH, APRIL, SEPTEMBER, AND OCTOBER
MAY, JUNE, JULY, AND AUGUST
YEAR
S
D
C
VECTOR-SCALE
0
10
20
30γ
X-Y PLANE
X-Z PLANE
D = MEAN DISTURBANCE-VECTOR
C = SUDDEN-COMMENCEMENT VECTOR
S = DIRECTION OF EARTH'S GEOMAGNETIC AXIS

FIG. 27.—Mean vectors for disturbances and sudden commencements, Watheroo Magnetic Observatory, 1919–30.

The average magnetic vector for all sudden commencements observed at Watheroo from 1919–30 (155 in all) is shown in Figure 27. It is compared with the mean storm-field vectors during the same period, obtained by subtracting the mean values of the elements on the five most disturbed days of each month from the corresponding values on the five most quiet days. The two vectors are almost diametrically opposed. Similar relations appear to hold at most other observatories, suggesting that the sudden commencements are reversed phenomena as compared with the main phase of magnetic storms.

(5) THE AFTER-FIELD AND NON-CYCLIC CHANGE

The changes, particularly the decrease in horizontal intensity, which occur during magnetic storms give rise to the phenomena known among magneticians as the after-field and non-cyclic change. Since horizontal intensity generally decreases during storms, the value of that element is, on the average, lower at the end of disturbed days than at the beginning. The storm, having completely died out, leaves the element below its normal value after which a fairly linear increase occurs in general until the next storm begins. This period of linear increase necessarily includes the most quiet days. The decrease on disturbed days and the increase on quiet days is the non-cyclic change, measured by the difference in the value of the element at the end of the day with respect to the beginning of the day. Thus the non-cyclic change on disturbed days is a decrease but on quiet days it is an increase. Contrariwise, the non-cyclic change in vertical intensity is an increase, numerically, on disturbed days and a decrease on quiet days. The interval during which horizontal intensity is below normal and vertical intensity is above normal is referred to as the post-perturbation period. These effects must be allowed for in making Fourier analyses of the variations. Spherical harmonic analysis reveals that non-cyclic change originates principally above the Earth's surface with induced effects within the Earth [315-*A*]. Both the internal and the external fields of non-cyclic change are closely representable by the first zonal harmonic about the Earth's axis of uniform magnetization.

(6) SOLAR-FLARE DISTURBANCES

Attention has recently been called to a special type of magnetic disturbance [1004, 1012] associated with cessation of high-frequency radio reflections from the ionosphere and simultaneous appearance of eruptions in the solar chromosphere. These disturbances are of great interest because they are the only terrestrial-magnetic events which have been definitely associated with events on the Sun, in spite of the intimate statistical relationship between magnetic storms and sunspots. They also serve to enhance understanding of various types of magnetic variations and the process of ionization by the Sun's light. Ordinarily the disturbance lasts for about 45 minutes or less, conditions at the end of this interval being the same as if the disturbance had not occurred. Figure 28 is a representation of the system of currents flowing in the upper atmosphere necessary to produce the magnetic effects observed at a large number of stations during the notable disturbance of April 8, 1936, compared with the normal diurnal-variation currents flowing at the time the disturbance occurred [1059].

Similarities exist between the normal diurnal-variation currents and the currents causing the solar-flare disturbances. The most striking feature is the close agreement of the two arrows at Teoloyucan which

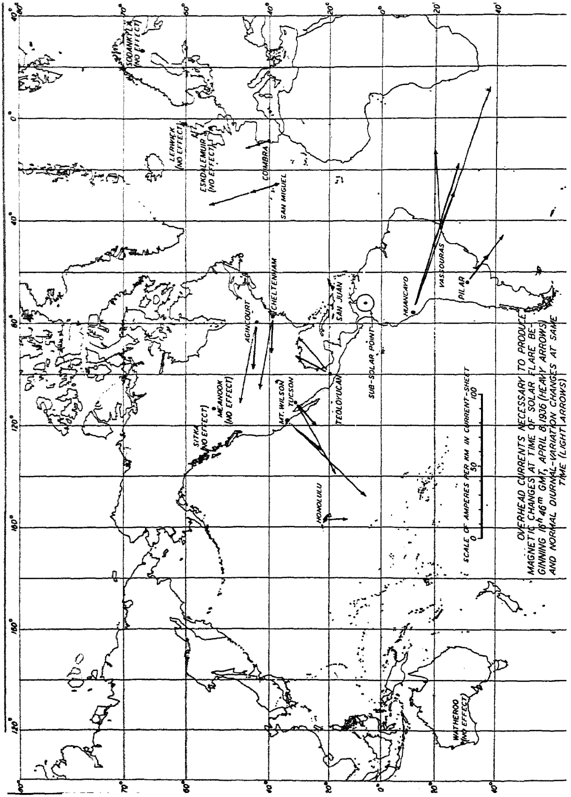


FIG. 28.—Overhead currents necessary to produce magnetic changes at time of solar flare beginning $16^h\ 46^m$ GMT, April 8, 1936 (heavy arrows) and normal diurnal-variation changes at same time (light arrows).

are oppositely directed to those at Mt. Wilson and Tucson. The change in direction of the diurnal-variation arrows normally occurs near San Juan at this time of day. On this particular day, however, the diurnal variation at Teoloyucan was anomalous, west declination increasing during the forenoon. This anomaly is faithfully reproduced by the solar-flare disturbance, demonstrating that the current-system of the solar-flare disturbance is an augmentation of the normal diurnal-variation current and not an independent circulatory system which merely simulates it.

If it is possible to show what levels of the ionosphere are affected by the chromospheric eruptions, important conclusions may be reached regarding the nature of the solar-flare disturbance and of the normal diurnal variation of which it is an augmentation. Fortunately, radio data are conclusive on this point [979]. They show radio reflections cease because of absorption of the radio waves in a region of new or enhanced ionization at the base of or below the *E*-layer, which is located at a height of about 100 km, while higher layers are not noticeably affected. This lower region must be where the currents of the disturbance and of the diurnal variation flow.

It is likely that the increased currents result from improved electrical conductivity of the region and are impelled by the electromotive forces of the normal diurnal variation which are continuously present. These facts strongly support the dynamo-theory of diurnal variation proposed by Balfour Stewart, for that theory supposes the continual presence of the electromotive forces. On the other hand, both the drift-current and the diamagnetic theories would lead to the expectation of increased ionization in higher levels. Furthermore, both theories fail to show why the field of the disturbance should reproduce the anomalies of the diurnal-variation system existing at the time of the chromospheric eruption.

The most pronounced magnetic effect during a solar-flare disturbance is observed at stations close to the sub-solar point at time of occurrence while no magnetic effect is observed at stations where the Sun's zenith-angle is 90° or over. Thus, these phenomena, being confined to the sunlit hemisphere, are markedly distinct from most magnetic disturbances which affect almost the entire Earth simultaneously and show greater variability in their incidence. The associated effects on radio transmission are similarly distributed.

(7) PULSATIONS

Frequently when the Earth's magnetic field is otherwise quite inactive small sinusoidal fluctuations are observed with periods from one to three minutes or even less and amplitudes up to about 5 γ. These phenomena, commonly called pulsations, occur most frequently around midnight [412]. A tendency to recur at intervals of 27 days has also been noted [408].

Close to the auroral zone, pulsations of unusual magnitude have been observed [405, 431]. They occur most frequently shortly after midnight.

During these pulsations the end of the magnetic vector at a given station describes an oval.

(8) THEORIES OF MAGNETIC DISTURBANCE

No adequate theory has been devised to explain magnetic disturbances. Close association of these phenomena with the Sun is established by the correlation of magnetic storms with the sunspot-cycle and by their tendency to recur at 27-day intervals—approximately the period of solar rotation. Except for the short-lived solar-flare disturbances, no close correspondence has ever been discovered between individual solar phenomena and magnetic disturbance. The solar-flare disturbances are entirely different in nature from world-wide magnetic storms.

Most theories of magnetic storms attribute them to the action of corpuscular radiation from the Sun. The direct electrical effect of a stream of electrons passing the Earth has been suggested [411] but the hypothesis is inadequate to account for the observed field-changes. Furthermore, such a stream would be deflected by the Earth's magnetic field in accord with the auroral theory of Birkeland [66] and Störmer [833].

Birkeland was able to demonstrate experimentally that electrons of certain energies projected at a magnetized sphere would reach the surface of the sphere in a zone around the magnetic pole, corresponding to the Earth's zone of maximum auroral frequency. The mathematical theory for determining the paths of the corpuscles was developed by Störmer. Birkeland conceived of magnetic storms as due to the direct magnetic effect of streams of charged corpuscles swerving down toward the Earth's surface and back out into space. These streams would give rise principally to the pronounced types of disturbance observed near the auroral zone which he called polar elementary storms. The negative phase of magnetic storms, involving the decrease in horizontal intensity in low and middle latitudes, would be caused by a ring-current formed around the Earth in accord with the mathematical implications of Störmer's theory.

The mathematical theory was developed for singly charged particles. Schuster [436] pointed out that a stream of corpuscles of one sign and of sufficient density to produce the necessary magnetic effects would disintegrate through electrostatic repulsion in traveling from the Sun to the Earth, although this consideration did not apply to streams of adequate density to produce the aurora. Lindemann [410] suggested that the stream might be electrostatically neutral, consisting of charged particles of both signs. It is not clear that such a stream would produce auroral phenomena.

The most recent development of this theory is due to Chapman and Ferraro [388]. They considered a neutral stream containing electrons and positive ions in which the Earth becomes entrapped, as shown in Figure 29. As this stream approaches the Earth, currents arise within the stream which restrain the Earth's flux from penetrating the stream and consequently increase the magnetic field outside the stream. This would cause the positive phase at the beginning of a storm. After the Earth has become fully entrapped, the electrons and positive ions circulate about the Earth in a great ring, producing the negative phase of the storm.

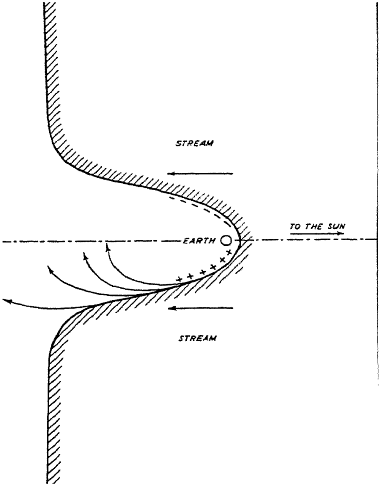


FIG. 29.—Envelopment of Earth in stream of corpuscles—equatorial section.

Although extensive calculations have been made, the theory is still in an unsatisfactory state.

Another aspect of the corpuscular theory involves heating of the high atmosphere by impact of solar corpuscles resulting in expansion, air-motions, and induction of currents by dynamo-action [377]. According to this conception the currents would be confined to the atmosphere, the corpuscular radiation being merely a stimulus for the terrestrial effects.

Probably the strongest argument against any corpuscular theory is the absence of convincing evidence from other sources (except the aurora) that the hypothetical corpuscular radiation exists. Eruptive prominences frequently observed on the limb of the Sun, most numerous at sunspot-maxima, suggest that clouds of corpuscles may be ejected from that body in the required manner, however.

This weakness of the corpuscular theory led to the proposal of an ultraviolet-light theory by Hulburt and Maris [406, 418] to account for aurorae and magnetic storms. According to this theory a sudden flare of ultraviolet light would excite the atoms and molecules of the upper atmosphere, which, by collisions of the second kind, would be thrown to extremely great heights. Some of these atoms and molecules would be ionized by the light-radiation and, spiraling down the lines of magnetic force, give rise to the aurorae. By means of several other effects involving transformation of long free-path regions of the ionosphere into short free-path regions and a consequent effect on the assumed drift-currents, the magnetic changes characteristic of magnetic storms are assumed to be produced.

The recent discovery of the special type of magnetic disturbance caused by bright chromospheric eruptions is strong evidence against the ultraviolet-light theory besides several other inherent weaknesses. The evidence is quite clear that the special solar-flare disturbance consists of an augmentation of the normal diurnal variation at all stations in the daylight hemisphere [1059] and is distinct from the disturbance associated with magnetic storms. These sudden increases in ultraviolet light have not given rise to magnetic storms. It is possible that ultraviolet flares of spectral distribution other than that of the bright chromospheric eruptions might produce magnetic storms, but such arguments are not cogent.

Corpuscular effects have been proposed to account for pulsations and bays. Störmer [831] has shown how corpuscular rays of certain energy might swing into and out of the Earth's magnetic field to produce these unique variations. From one point of view, magnetic bays may result from direct magnetic effects of charged corpuscles [443, 448]. On the other hand, heating of the atmosphere in the auroral zone by incoming corpuscles may give rise to winds which, in view of improved conductivity through corpuscular bombardment, might produce intense currents in that region. Closure of the currents through paths lying in middle latitudes would give rise to the effects observed there [415].

While theories of the diurnal variation seem in a fairly satisfactory state, theories of magnetic storms are open to much argument. No reasonably adequate theory to explain these phenomena has been proposed. The rapidity with which our knowledge of the ionosphere is advancing warns against dogmatic views and makes research in this field a source of continual inspiration.

CHAPTER VIII

SOME PROBLEMS OF TERRESTRIAL MAGNETISM AND ELECTRICITY

J. Bartels

Geophysical Institute, University of Berlin

I. INTRODUCTION

The object of terrestrial magnetism and electricity is the observation and investigation of all natural magnetic and electric phenomena concerning the Earth and its atmosphere. This generally implies extensive application of other physical, geophysical, and astrophysical knowledge. Earth-currents and aurorae are generally treated in connection with terrestrial magnetism, and the study of lightning with atmospheric electricity. For historical and other reasons, certain groups of electromagnetic waves, such as radiation of light or heat, are assigned to other branches of geophysics. Accordingly, those problems presented here are selected not only because of their importance to scholars specializing in the Earth's magnetic and electric fields, but also because they may be expected to invite the attention and cooperation of investigators in pure and applied physics, geology, geophysics, astrophysics, and mathematics.

In general, very loose connection, if any, has been found between terrestrial-magnetic and atmospheric-electric phenomena as directly observed near the Earth's surface. This lack of interrelation is inherent and not due merely to imperfect knowledge. Atmospheric-electric conditions depend largely on the locality (sea, mountain, valley, etc.); they change fundamentally with fair, cloudy, or foggy weather near the point of observation and are violently disturbed during the passage of squalls and thunder-storms. Atmospheric electricity, reflecting the more or less irregular and intricate succession of conditions of weather, therefore shares with meteorology and climatology the local or regional character and the lack of correlation between phenomena occurring simultaneously in different regions of the Earth. Terrestrial magnetism is also locally affected in so far as the average magnetic field is connected, to a certain extent, with the underlying geological structure. But all magnetic variations—by which we shall always designate time-changes—are remarkably independent of local conditions and of the weather. This is especially so for the most violent perturbations—the magnetic storms—which occur more or less simultaneously and with the same characteristic features all over the Earth.

The cause for this fundamental difference in the electric and magnetic variations can be definitely stated: The origin of the main electric variations is in the lower atmosphere, up to a height of perhaps 20 km. The magnetic variations, however, are produced by electric phenomena in the highest regions of the atmosphere—above 60 km—called the ionosphere because of the high content there of electrified particles, ions, and electrons. The ionosphere, as the outermost region of our planet, is highly affected by solar influences of two kinds, namely, (1) sunlight of short wave-length and of great ionizing and dissociating power and (2) the impact of solar particles visibly indicated in aurorae. These solar influences vary in intensity with the growth and decay of active regions on the Sun's surface and their changing geometrical position toward the Earth; but if they affect the ionosphere at all it is either in its whole extent or in large regions. It thus appears that the usual distinction between terrestrial magnetism and electricity is only traditional, based on the phenomena observed near the ground, and that these phenomena lack correlation in so far as there is no appreciable interaction between the ionosphere and the lower atmosphere.

This opinion, however, is subject to modification. In fact, C. T. R. Wilson's outline of a possible connection between the ionosphere and thunder-storms [961], or the tendency to 27-day recurrence in atmospherics (see section III-6) may eventually lead to the detection of common features in terrestrial magnetism and atmospheric electricity.

II. RELATIONS TO THE IONOSPHERE

(1) Ionosphere anticipated from observations of the Earth's magnetism

The discovery of the ionosphere is perhaps the most important result of systematic observations of terrestrial magnetism and their theoretical considerations. We shall therefore consider, first, questions relating to the upper atmosphere, leaving those relating to the solid Earth until later. In these years, in which experiments on the propagation of electromagnetic waves provide a new powerful tool in the study of the ionosphere, it is perhaps of interest to recall some of the earliest indications in the literature bearing on the Earth's magnetism. In C. F. Gauss's "Allgemeine Theorie des Erdmagnetismus" (1838), article 36 reads as follows:

> Another part of our theory, about which a doubt is possible, is the assumption that the agencies of the terrestrial-magnetic force are confined to the interior of the Earth.
>
> If we should look for the direct causes, completely or partly, in the exterior, we could —if we exclude baseless fancies and keep to scientific knowledge—only think of galvanic

currents. The atmospheric air is no conductor of such currents, neither is the vacuum. Our knowledge therefore leaves us in the dark about a conductor for galvanic currents in the upper regions. However, the mysterious phenomena of the aurora, in which, to all appearances, electricity in motion acts the main part, forbid us to deny outright the possibility of such currents only because of the uncertainty mentioned and it is, in any case, interesting to study how the magnetic effect of such currents would appear near the Earth's surface.

After a mathematical treatment, Gauss goes on to say (article 41) that the study of the terrestrial-magnetic variations of terrestrial magnetism—the regular diurnal as well as the irregular changes—should possibly yield the first definite evidence in this respect. The observational material accruing in the following 40 years enabled Balfour Stewart in 1878 (see Chapter IX) to conclude, from a discussion of the diurnal magnetic variations, that they originate in the upper atmospheric layers and that the air in these layers must conduct electricity much better than the air near the ground. A. Schuster gave the exact mathematical verification of these fundamental ideas and indicated ultraviolet light as the possible ionizer.

(2) SOURCES OF KNOWLEDGE IN THE IONOSPHERE

Much later, but apparently quite independently, the existence of an ionized layer in the upper air was proposed in explanation of Marconi's successful transatlantic radio communication in 1901; this is why the ionosphere is so often associated with the names of A. E. Kennelly and of O. Heaviside. Since the pioneer experiments, in 1925, of Appleton, Breit and Tuve, and others, verifying in the most direct manner the existence of a conducting atmospheric layer, wireless research on the structure of the ionosphere has revealed much information, partly corroborating the terrestrial-magnetic evidence, partly supplementing it. Thus our present knowledge of the ionosphere is based on three main sources, namely, terrestrial-magnetic records, wireless experiments, and auroral observations. In an attempt to state those problems which might be elucidated with the help of terrestrial magnetism, we shall have to refer to the accounts of the physics of the ionosphere in the light of radio and auroral exploration (see Chapters IX, X, and XI).

III. TERRESTRIAL-MAGNETIC ACTIVITY AND THE SUN

(1) TERRESTRIAL-MAGNETIC ACTIVITY AND ITS CHARACTERIZATION

In comparison with the other means of exploration of the ionosphere (radio and auroral), terrestrial magnetism is favored in two respects: (1) magnetic observatories record continuously, without interference of daylight, season, or conditions of weather; and (2) they are distributed in a network which, although it cannot be considered as ideal, represents the magnetic conditions all over the globe in a fairly complete manner. Under these circumstances, the task of continuously recording the occurrence and intensity of solar influences on the ionosphere falls to terrestrial magnetism; this gives a significance to that otherwise trivial measurement of the degree of magnetic disturbance, usually called magnetic activity [272].

The simplest scheme of measuring magnetic activity as adopted at present is as follows: Each observatory assigns, on the basis of the character of its magnetic records, to each interval of 24 hours between successive Greenwich midnights, a character-number, namely, "0" for quiet, "1" for moderately disturbed, and "2" for greatly disturbed days. The average for all collaborating observatories (the number of which increased from 30 to about 50, since this measure was begun in 1906) is the international magnetic character-figure *C*, usually given to one decimal.

That on so many days practically all observatories report character "0," and, during great magnetic storms, all report "2," proves the world-wide nature of magnetic activity as well as the adequacy of the simple procedure for deriving *C*. However, a certain limitation in the use of *C* must be indicated. For example, for the two days, April 1 and 18, 1910, *C* is given as 1.3 and we may safely accept these days as about equally disturbed; but we should hesitate to say the same for April 12, 1930, though *C* is again 1.3. For there is no safeguard that the standard of characterization may not have shifted within the 20 years from 1910–30. We shall later refer to more objective measures of activity and find that such inadvertent shifts in the standard of *C* may occur—less frequently, however, than might have been anticipated. For the comparison of days within a few months or a year, *C* is satisfactory, as we shall see presently.

(2) TENDENCY TO 27-DAY RECURRENCE

Magnetically quiet or disturbed times extend, in general, over a few days in succession and, moreover, do not alternate quite at random. There is predominantly a strong tendency of recurrence after about 27 days, which is easily recognized in the diagram of Figure 1. Each day is represented by a square area, which is left blank for very quiet days, while the various degrees of magnetic activity are indicated by symbols, leading up to a block square for highly disturbed days. These squares are put together in rows, forming a tessellar mosaic which can be read like a book. The date of the first day in each row is given at the left. A new row is begun after every 27 days, so that the vertical columns represent days with the intervals 27, 54, 81, etc; for clearness, the first six days of the next row are added at the right.

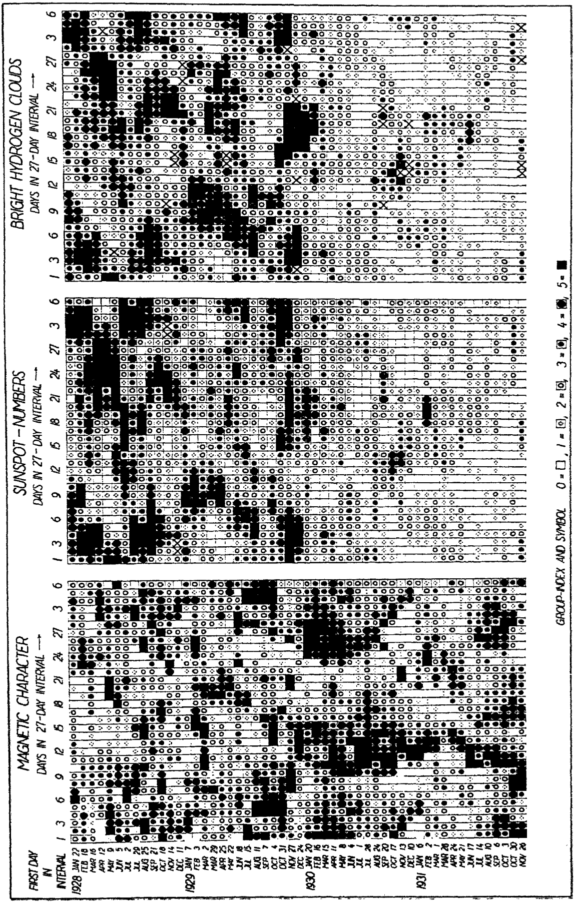


FIG. 1.—27-day recurrences in terrestrial-magnetic activity and solar phenomena.

The tendency for a 27-day recurrence is clearly expressed in the vertical columns indicating sequences of quiet or disturbed times. A slant in the columns marks a shorter or longer recurrence-interval, for instance, of 26 days, if the column slants by an angle of 45° downward towards the left. Fine sequences of disturbed days occur in 1923 and 1929–32, while in the years 1924–28 the disturbed days seem to recur less persistently.

(3) THE SUN'S *M*-REGIONS

The explanation of this phenomenon of 27-day recurrence in magnetic activity is based on the fact that the Sun's surface has a rotation-period of the same length. This rotation makes sunspots disappear round the west limb of the Sun; if they live long enough, they reappear at the east limb and cross the central meridian—as viewed from the Earth—after an average interval of 27 days. More exactly, this interval depends on the solar latitude (distance of the spots from the solar equator), increasing from 26.9 days for the equator to 27.1, 27.5, 28.3, and 28.8 days for spots in 10°, 20°, 30°, and 35° latitude, respectively.

The general idea [383, 387, 388] is that streams or clouds of solar particles—atoms and molecules in neutral or ionized state—are emitted from certain active regions on the Sun's surface. In their succession these particles form a more or less continuous jet, not unlike water from a revolving garden-hose, and every time this jet sweeps across the Earth in its orbit the particles penetrate into the ionosphere and cause auroral and magnetic disturbances. After several rotations, the supply from the source on the Sun—called "*M*-region," for abbreviation—is exhausted, while another *M*-region persists or is newly formed.

Sunspots appear, at the beginning of an 11-year cycle, in high heliographic latitudes (30°). With the progress of the cycle, new spot-groups are formed in decreasing latitudes, till the last spots of the cycle vanish near the Sun's equator at the end of the cycle, while, sometimes, the first spots of the next cycle are already visible in high latitudes. Since the plane of the Earth's orbit is only slightly inclined to that of the Sun's equator, radial solar streams of particles might be expected to sweep across the Earth more persistently toward the end of an 11-year cycle, that is, in the years between maximum and minimum of sunspots. This is confirmed by the observations. For instance, fine 27-day sequences in the first half of 1923 and in the years 1930–33 stand out against the spotty appearance of the diagram in the intervening years of the cycle. The transition from the old to the new cycle, so marked in 1923, has been found also in the earlier cycle.

In order to test and elaborate this simple conception, various inferences have been deduced from it and compared with the observations. A small number of single cases of coincidence between solar eruptions and the following outbreak of a terrestrial-magnetic storm, after about a day, have been described by Hale [404]. But though this collection is a valuable addition to our knowledge and deserves to be continued, there are also singular failures on record, so that it seems best to rely only on conclusions drawn from a large observational material. This reserved attitude, imposed by the experience of most workers in this field, seems justified, for observations in the years 1924–28 or 1934–38 would never have suggested the possibility of such persistent sequences as found from 1929 to 1933.

Chree and Stagg [298] have attempted to determine the length of the recurrence-interval more accurately. For each disturbed day (five disturbed and five quiet days are selected per month, indicated as most disturbed or quiet by the international character-figure *C*) they copied a row of figures *C* for the 25th to the 29th day, 52nd to the 56th, 79th to the 83rd, 106th to 110th day before and after it. The average of all rows shows increased activity on the 27th, 54th, 81st, and 108th days. The corresponding computation was applied to all quiet days. The result is reproduced in Figure 2. The recurrent "pulses" fall so near exact multiples of 27 days that no deviation from that interval can be detected. Years with sunspots in high and low latitudes were investigated separately but did not reveal a lengthening of the recurrence-interval with spots in higher latitudes, which is rather puzzling because of the decided increase of the period of rotation of the solar surface with solar latitude, mentioned above.

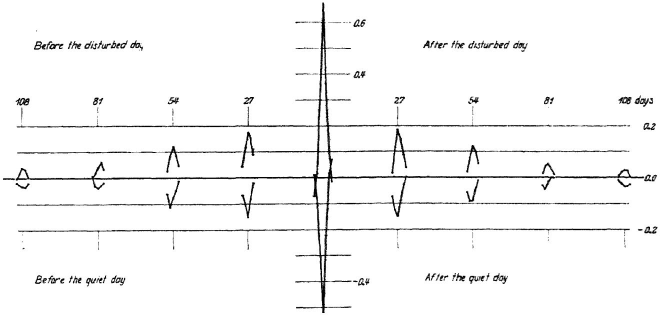


FIG. 2.—Deviations from average 0.62, mean international magnetic character-figures for groups five to seven days around disturbed or quiet day and for such groups one, two, three, and four days preceding and following solar rotations (*after Chree and Stagg*).

Greaves and Newton [403] have made similar calculations on the basis of a catalogue of all magnetic storms (about 400 in number), during the years 1874–1927. They classified them in five groups of decreasing intensity and found (Fig. 3) that the really great storms—changing the terrestrial-magnetic field at Greenwich by more than about $\frac{1}{200}$ of its normal value and which would be designated by international character-figures 1.9 or 2.0—do not show any tendency for recurrence. This tendency is in fact a peculiarity of moderate disturbances only. This is apparent also in diagrams like Figure 1; for instance, it shows in the second half of 1923 some isolated great storms in the midst of quiet sequences. Those solar eruptions which cause the greatest magnetic storms, therefore, do not seem to survive a solar rotation, but the weaker active areas live longer.

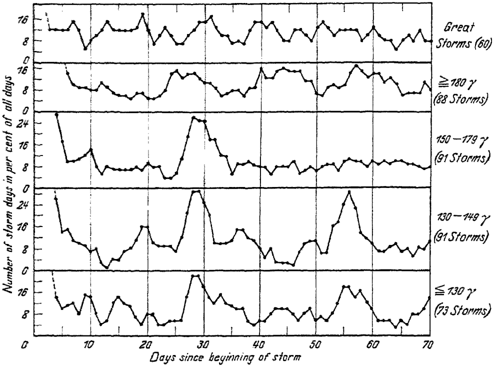


FIG. 3.—Average frequency of magnetic storms within 70 days after the outbreak of a storm, separated in five groups according to the intensity of the first storm (*after Greaves and Newton*).

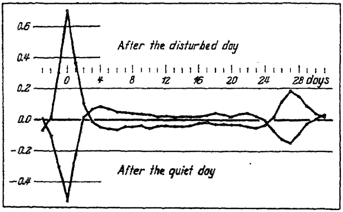


FIG. 4.—Deviations from average 0.62, mean international magnetic character-figures, from four days before until 31 days after disturbed or quiet day (*after Chree and Stagg*).

A regular subdivision of the Sun's circumference by the active areas is not indicated in Figure 4, because there is no sign of a corresponding subdivision in the magnetic recurrence-interval.

(4) COORDINATION OF INDIVIDUAL SOLAR AND TERRESTRIAL PHENOMENA

On the assumption that the solar origin of magnetic disturbances is proved by the recurrence-tendency, the next step is the direct coordination of each single disturbance with an observed phenomenon on the Sun's surface.

This has been attempted, for instance, by Greaves and Newton [402]. They determined the occurrence of the highest degrees of terrestrial-magnetic and of solar activity by selecting, from their catalogue of magnetic storms, 60 storms which changed the magnetic field at Greenwich by more than $\frac{1}{50}$ of its average value, and, for comparison, the 455 groups of sunspots visible to the naked eye (covering more than one two-thousandth of the Sun's disk) during the same years (1874–1927). Thirty-six storms of the 60 began within four days before and four days after the passage of one of the spot-groups across the Sun's central meridian. If only the 17 storms of the highest intensity (changing the field by more than $\frac{1}{30}$ of its average value) were considered, all except two were found to coincide, in the way described, with spot-groups.

Therefore it seems that, for the great storms, certain restricted areas of the Sun's surface, near the spot-groups, may be considered as the source of the corpuscular stream in most cases. This rule points so clearly to a relation of cause and effect that failures of coincidence must be considered as exceptions—striking as they may be. Two kinds of such exceptions are known: Magnetic storms occurring at times when the Sun was perfectly free of spots (for instance, the storm of January 29, 1924, while sunspot-number 0 was recorded from January 6 to February 13), and large sunspots without any effect in terrestrial-magnetic activity (for instance, the spot covering $\frac{1}{600}$ of the Sun's disk, crossing the central meridian on June 16, 1905). In the other cases in which the identification was rather certain, the storm began, on the average, about a day after the spot crossed the central meridian (see G. E. Hale's list [404], mentioned previously).

J. M. Stagg [440] and Ch. Maurain [423, 425], in extensive statistical studies, found a relative maximum of solar activity between two and three days before terrestrial-magnetic disturbances.

(5) RELIABILITY OF MAGNETIC CHARACTER-FIGURE AS AN INDEX FOR SOLAR ACTION IN THE EARTH

Since the ordinary (moderate) degrees of magnetic activity are known to show the tendency to 27-day recurrence even more clearly than the infrequent large storms, for which the coordination to individual sunspots has been so successful, the same task for the moderate disturbances would seem to be easier. Strangely enough, the attempt at a coordination of recurring disturbances to long-lived sunspots has been a signal failure so far. Similar diagrams for detecting 27-day recurrences as that for terrestrial-magnetic activity have been drawn in Figure 1 for two other measures of solar activity—sunspot-numbers and character-figures for hydrogen clouds. Distinct columns indicating recurrent active areas on the Sun appear and are easily identified in the various diagrams representing direct solar observations, but no relation can be detected between these and the individual recurrent series of magnetically disturbed days, even if the possibility of a time-lag is kept in mind!

This result lends a new significance to moderate magnetic activity, occurring on days with international character-figures between, say 0.8 and 1.4; since one-third of all days belong, on the average, to this class, this type of moderately disturbed conditions is a quite common phenomenon. Its pronounced recurrence-tendency points to its origin in definite areas on the Sun's surface—already mentioned as M-regions—but these areas cannot be easily identified on the Sun by the usual astrophysical observations and can as yet be traced only in their effect on terrestrial magnetism.

Observations with the spectrohelioscope, invented by Hale, are being taken up at several astrophysical observatories and organized to insure a more or less continuous spectrohelioscopic watch. This should bring the solar observations more in line with the well-organized records of terrestrial magnetism. By registering a greater number of the sudden solar flares it has already been possible to collect more cases of individually coordinated solar and terrestrial-magnetic phenomena. Radio fade-outs, occurring simultaneously with solar flares, have drawn the attention to simultaneous, well-defined magnetic variations. This discovery (see Chapter IX) has definitely shown the magnetic effect of an increase in solar wave-radiation as *not* being that of ordinary disturbance, for the cause of which the assumption of corpuscular radiation thereby appears strengthened.

(6) 27-DAY RECURRENCE IN OTHER PHENOMENA—ATMOSPHERICS

The recurrence-tendency can be traced also in those phenomena which are closely correlated with terrestrial-magnetic activity, for instance, in aurorae or earth-currents.

Schindelhauer [1096, 1097] has found indications for the recurrence-tendency in the frequency of "atmospherics" or "statics" of wireless telegraphy. He supposes [383, 387] that these atmospherics originate when solar particles penetrate into the ionosphere. R. A. Watson Watt

[961], however, believes that the number of atmospherics is an indication of the thunder-storm activity within a neighborhood the radius of which depends on the state of the ionosphere from which the electromagnetic disturbance (received as atmospheric) is reflected toward the Earth. Thus the 27-day recurrence-tendency in the number of atmospherics received at a given station might be explained, not by an increased number of disturbances per square mile, but simply by a similar variation in the effective reflection-coefficient of the ionosphere, without involving an ionospheric origin of the atmospherics.

(7) RECURRENCE-TENDENCY AS MODEL OF QUASI-PERSISTENCE

The more or less irregular interference of various influences, which is so typical for all time-functions representing the results of geophysical or meteorological observations, is also exhibited in terrestrial magnetism. The statistical methods needed for successful analysis of such functions are of a special nature which prevents simple application of such schemes as have been developed in connection with statistical studies in mathematics, physics, or biometry.

Indeed, one of the main problems, the investigation of hidden periodicities, has been treated for a long time with insufficient and even misleading methods. Only the alternative "random fluctuations" (corresponding to the results of playing dice) and "persistent waves" (perfectly periodic functions of the type of the sound-waves produced by the vibrations of one or more tuning forks) had been considered, while no satisfactory statistical method was available for the intermediate types of finite trains of waves with changing phases. The classical example for these very common types is the 27-day recurrence-tendency in magnetic activity. The general conception of "quasi-persistence" [361] has been developed from this interesting material, although, in its physical nature, it has no inherent relation to sine-waves. Quasi-persistence, in its various modes of appearance, is found to be of importance for many applications of the theory of probability to geophysical and other problems. A number of questions of mathematical and geophysical nature await solution in this field which shows harmonic analysis in a new light and, at the same time, gives the means to generalize it so as to exclude explicit reference to sine-waves.

(8) THE u-MEASURE OF MAGNETIC ACTIVITY

So far, we have confined the discussion to the times when magnetic disturbances occur. Reserving the question of the actual magnetic variations during storms (the morphology of magnetic disturbances, so to say) and their physical theory to later sections, the next step—if we want to look more closely into the relations between solar and terrestrial-magnetic phenomena in the course of the 11-year period of sunspots—will be to derive an *objective* measure of magnetic activity. This should be free from the uncertainty of the international character-figures, C, and it should be easily derived for the years before 1906, that is, before the international scheme of characterization was introduced.

The definition of such a measure [272] must be based on a certain knowledge of the morphology of storms. The simplest way would seem to be to start with ranges, that is, differences between the greatest and smallest values reached by, say declination or horizontal or vertical intensity within an interval, such as an hour or a day. These ranges, however, do not lead to a satisfactory measure of activity, because, for quiet days, they are completely governed by the regular diurnal variation and therefore subject to its large and systematic changes with the season, which are not easily eliminated. Therefore, satisfactory monthly and annual means of magnetic activity are based on the fact that the horizontal portion of the Earth's magnetic force varies from day to day very similarly all over the globe, rapidly decreasing during a magnetic storm and slowly recovering afterward (see Chapter I, Fig. 46). The u-measure of activity is the average change from day to day, regardless of sign, of the daily means of the magnetic force H_0 near the Earth's equator. H_0 is, in absolute units, about 0.34, or, in the 100,000 times smaller unit, γ, used in terrestrial magnetism, $34{,}000\gamma$; since 1900, the highest and lowest monthly means of activity were May, 1921 ($u = 27.0\gamma$) and July, 1913 ($u = 3.8\ \gamma$).

For some purposes, a slightly modified measure, u_1, of magnetic activity is more adequate. u_1 is simply a function of the monthly means of u, namely, a linear function for small values of u (with u measured in γ, $u_1 = 10u - 3$, up to $u = 7\gamma$), but it increases less rapidly for higher values and never exceeds 140. u_1 has been chosen so that its frequency-distribution is about the same as that of the relative sunspot-numbers.

Annual means (see Chapter I, Fig. 43) and monthly means (see Chapter IX, Fig. 2) of magnetic activity, C, in comparison with relative sunspot-numbers, R, show the well-known 11-year cycle in both solar and magnetic activity. This parallelism is by far the closest relationship between any solar and geophysical phenomena. The correlation-coefficients, for the years 1872–1930, between u_1 and R are +0.884 for annual means and +0.654 for monthly means. The mathematical treatment of these relations offers an interesting example in the theory of statistics in so far as the consecutive annual or monthly means are clearly not independent; in such cases, the usual correlation-coefficients can lead to erroneous interpretation. If, for instance, we form, for u_1 and R, the departures of the monthly means from their respective annual means, the correlation-coefficient for these departures is only +0.292. This points to the following feature of the relationship: Near the maximum of solar activity in the 11-year cycle, both solar and terrestrial-magnetic activities are high, and near the minimum, both are low; this accounts for the good correlation of the annual means. However, the shorter, irregular fluctuations—of the order of a few months—superposed on the 11-year cycle of sunspot-activity, are only poorly reflected in terrestrial magnetism. The general formulas for relations of this type—frequent in geophysics and meteorology—have been developed and could be useful in many similar cases [272].

(9) SEASONAL VARIATION IN MAGNETIC ACTIVITY

Seasonal changes in terrestrial magnetism differ in character from those in meteorology (for example, atmospheric temperature) in so far as the average values of the intensity and direction of the Earth's magnetic force are only slightly affected; but the regular diurnal magnetic variation has generally greater amplitude in summer and changes its appearance from summer to winter.

As we have seen, magnetic activity is a world-wide phenomenon, and it is therefore not likely that activity should differ systematically during summer or winter on the two hemispheres. This is, to a certain extent, confirmed by the long series of the u_1-measure. In the first days of January, the Earth is nearest to the Sun and intercepts about six per cent more solar radiation than in the first days of July; a similar 12-month period in magnetic activity might have been expected but is apparently too small to be traced in the observations. The predominant feature of the annual variation of magnetic activity is a pronounced double wave, a six-month period (see Chapter I, Fig. 44-*A*); harmonic analysis reveals, for the average of the years 1872–1930, two maxima, corresponding to $u_1 = 57$, in the first days of April and October, and two intervening minima, corresponding to $u_1 = 44$, in the first days of January and July.

The "equinoctial maxima" of magnetic activity offer a puzzle for a satisfactory explanation. The equinoxes—the Sun's crossings of the plane of the Earth's equator—occur about March 21 and September 23. But only about 16 days earlier there are two other remarkable astronomical features, namely: The Sun's surface rotates about an axis which is inclined $7\overset{\circ}{.}2$ to the ecliptic, so that, in the course of the year, the radius connecting the Sun's center with the Earth cuts the Sun's surface in varying heliographic latitudes, attaining $7\overset{\circ}{.}2$ north about September 7, and $7\overset{\circ}{.}2$ south about March 5.

The observational evidence on the six-month period in magnetic activity speaks in favor of the equinoxes as the times of the maxima, and not for the earlier dates. However, theoretical considerations have been brought forward which would point to the earlier dates. These are based on the fact that sunspots occur most frequently in heliographic latitude 10° to 15°, while the Sun's equatorial belt is comparatively free of spots. Suppose the corpuscular solar streams to start from the same belts in which the sunspots occur and to leave the Sun's surface in radial direction or, at least, in directions lying on the cone from the Sun's center to the circle of latitude; then the streams emitted from the northern spotted belt would be more likely to sweep across the Earth in September, and the southern streams in March. This would, if the streams were narrow enough, account for the six-month period and would be in keeping with the feature of the 27-day recurrences mentioned above.

This explanation, however, meets a serious difficulty in the following independent test [272]. The two hemispheres of the Sun vary, to a certain degree, independently in the 11-year cycle. For instance, for years in succession the Southern Hemisphere has shown more sunspots than the Northern Hemisphere (thus in the years 1883–89, 1895–1900, 1907–12). In such years, the arguments used above would lead us to expect comparatively higher magnetic activity, u_1, around March than around September, and vice versa. The asymmetry in the distribution of the sunspots is so large that it was possible to select about 30 equinoctial months in which, on the average, the hemisphere in question (the southern in February, March, April, the northern in August, September, October) had disturbed areas double the extent of the other, and 30 other months, in which the distribution of the sunspots seemed unfavorable for producing terrestrial-magnetic effects. Yet not the slightest systematic difference in u_1 could be discovered!

(10) DIURNAL VARIATION OF MAGNETIC ACTIVITY

A diurnal variation of magnetic activity has been found, for instance, by J. M. Stagg [438] for London. Similar to the scheme for the characterization of days, he assigned character-figures, 0, 1, and 2, to each hour. The quietest time of the day is, throughout the year, about noon. Moderate disturbances are most frequent shortly after midnight, while character-figures 2 are most frequent in the evening—in winter about 22^h, in summer about 18^h. Similar investigations for other stations are desirable.

It is not easy to give exact numerical definitions of activity for hourly intervals, because the regular diurnal variation interferes even on quiet days. Yet further work in that direction seems promising, because there are indications [268] of a universal-time diurnal variation of magnetic activity, affecting the Earth as a whole. Since the Earth's magnetic axis is inclined, by 11°5, toward the axis of rotation, its angle with the radius connecting Sun and Earth, that is, with the direction of the solar streams, varies in the course of a day. In June, for instance, the angle is 78° about 5^h GMT, and only 55° at 17^h. The solar streams are deflected by the Earth's magnetic field, and it is quite probable that the varying orientation of the great magnet, Earth, is of influence in the development of magnetic disturbances.

IV. GENERAL FEATURES OF A MAGNETIC FIELD

(1) Separation of interior and exterior parts

In order to discuss the actual physical processes involved in terrestrial magnetism, it is necessary to localize the sources of the magnetic time-changes so far as possible. The general methods are given below.

Every magnetic field, F—that is, a distribution of magnetic forces in space—is produced either by magnets or by electric currents or by both. A given arrangement, say A, of magnets and currents causes a well-determined magnetic field, F. However, this relation does not hold in the inverse direction. Thus if such a magnetic field is known in a certain volume of space, there can be an infinite number of arrangements, A, each of which would produce the same field, F, but it is not possible to single out the actual arrangement without additional evidence besides F. This holds even in the simplest case, when no time-changes occur.

This ambiguity presents a fundamental difficulty to all theories of terrestrial magnetism. Under two conditions, however, potential-theory allows a very important inference to be drawn from the observational material. These conditions are (*a*) that simultaneous values of the magnetic field, F (given, for instance, by rectangular components, X, Y, and Z, measured northward, eastward, and downward, respectively), are known all over a spherical surface surrounding the Earth, and (*b*) that no natural magnets and no electric currents of appreciable magnetic effect occur in or near this surface.

Then F can be divided up into two parts, F_i and F_e, the origins of which are interior and exterior to the surface, respectively. The separation is effected by means of spherical harmonic analysis, a purely mathematical process involving development into series of terms of spherical harmonics and introduced into terrestrial magnetism by C. F. Gauss. The exterior part, F_e, may be mathematically represented as the effect of a system of electric currents flowing in a sheet in the ionosphere at a height which remains indeterminate, as far as terrestrial-magnetic observations go.

This "equivalent current-system" is only a convenient means of illustration and not necessarily an expression of the actual physical causes of F_e. The supposition (*a*) that F is known all over the globe, to a certain extent, is justified by the fact that the records of a single magnetic observatory represent the magnetic variations over a rather wide neighborhood (see section I), say (according to the phenomenon considered) one one-thousandth to one one-hundredth of the Earth's surface. This holds especially for equatorial regions. In the polar zones, however, magnetic time-changes may differ greatly within a few hundred miles; unfortunately, observatories and field-observations in these regions are few. The uncertainty thus introduced by the scarcity of polar observations is not equally serious for various questions, but it must not be overlooked.

The second condition (*b*) implies that no electric currents flow in the immediate vicinity of the Earth's surface, so that the magnetic field has a potential. The vertical currents of varying intensity observed by the methods of atmospheric electricity may seem to contradict this condition. In this case, another term, a non-potential field, N, must be introduced, which makes the separation

$$F = F_i + F_e + N$$

indeterminate. This point has obtained considerable attention both from the magnetic and from the atmospheric-electric standpoints; fortunately, as will be explained later, the vertical currents seem to be so weak that N can be neglected.

Finally, the Earth's ellipticity (its polar radius being about 21 km shorter than the radius of the equator) implies a formal, though rather intricate, development of the usual scheme of spherical harmonic analysis if the highest accuracy is desired. For these details we refer to the classical papers of Adolf Schmidt [47].

(2) CONVENTIONAL SUBDIVISION OF MAGNETIC PHENOMENA

A usual way of subdividing F allows for the time-scale appropriate to various, more or less conventionally defined terrestrial-magnetic phenomena. From the instantaneous values of F at a given moment, averages for various intervals of time are formed and ascribed to the middle of the interval. Thus there are the annual mean (also called the normal value) and monthly, daily, and hourly means. The distribution of the normal values, for a given year, over the globe is called the permanent field—a somewhat euphemistic expression, because there is an appreciable change of the normal values from year to year, called secular variation.

The time-changes of the instantaneous value, F, can be apportioned to the various phenomena by forming "deviations" of the average for the shorter interval from that for the longer interval—for example, monthly deviation is monthly minus annual mean. Thus, we may write the following simple "chain":

Instantaneous value F
= Secular value (average for ten years) $= F_0$
+ [annual mean minus secular value] $+ F_1$
+ [monthly minus annual mean] $+ F_2$
+ [daily minus monthly mean] $+ F_3$
+ [hourly minus daily mean] $+ F_4$
+ [instantaneous minus hourly mean] $+ F_5$

or something equivalent. Such simple separations, in themselves, are purely mathematical and must be justified by the way in which they help us to understand the physical processes involved.

Each of the partial fields (as formed by the deviations) can be separated for itself into interior and exterior parts, at least theoretically. The ratio of the exterior to the interior part is found to be small in the permanent field (roughly 1 to 100), so that the origin of the permanent field must be inside the Earth's surface. A spherical harmonic analysis [335] of the secular variation fails because of the incomplete data. However, a simple consideration leads also to the assumption of mainly interior origin, because, in the course of centuries, the secular variation adds up to appreciable portions of the permanent field (magnetic declination at London 11° east of north about 1580, 24° west of north about 1800, 12° west at present), so that it is highly improbable that the secular variation represents a change of the small exterior part of the permanent field. In contrast, the other variations of shorter period seem to be mainly of external origin—the small 11-year cycle, F_1, the annual variation, F_2, the consecutive daily deviations, F_3 (the basis of the u-measure of activity, section III-8), the diurnal variation, F_4, and the rapid oscillations, F_5, as well as the disturbances which affect all partial fields. Even the secular variation, calculated from annual means, is not entirely free from the influence of activity [346], because of the different frequencies of disturbances and their systematic effect on the average field (see section III-10) in the course of the 11-year cycle of sunspots; therefore Adolf Schmidt [see Chapter XIII, section V—Potsdam] introduced averages for F for ten years, in which the effect of the 11-year cycle is practically smoothed —he called them "secular values" and their annual change the "true" secular variation.

V. MAGNETIC STORMS

(1) The average magnetic storm

The aspect of individual magnetic storms differs widely, not only when a certain storm is compared at different localities but also when several storms at one and the same station are compared. There are, however, common features. For instance, many storms start from quiet conditions with a sudden jerk, simultaneous within a minute of time all over the Earth. N. A. F. Moos [43], for Bombay during 1882–1905, lists 347 storms lasting at least five hours, with a range, in horizontal intensity, greater than 78 γ; 113 of these storms, that is, about one-third, have such distinct "sudden commencements." These do not seem to prefer a definite time of the day but may occur at any hour. We may call "storm-time" the time reckoned, in hours, from the commencement and obtain, by superposition of all storms, the typical curves for the average magnetic storm as a constituent of the magnetic variations.

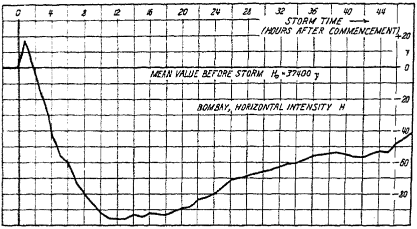


FIG. 5.—Average magnetic storm as recorded in horizontal intensity (H), Bombay Observatory (*after N. A. F. Moos*).

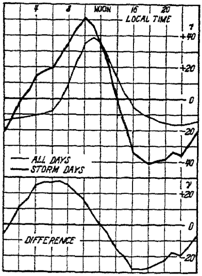


FIG. 6.—Mean average diurnal variations of horizontal intensity (H), Bombay Observatory, for all days and for storm-days, and difference of the two curves (*after N. A. F. Moos*).

In this average curve, which is most characteristic in horizontal intensity, H (Fig. 5), all individual features of the single storms are smoothed, and also the influence of daylight hours. The average storm begins with a sudden rise of H, lasting a few minutes up to a fraction of an hour, followed by a fall lasting 8 or 12 hours, and ends with a recovery which gets slower gradually and is cut off by the next disturbance. This phenomenon is also reflected in the consecutive daily means of H (see Chapter I, Fig. 46) and has been chosen as the basis of the u-measure of magnetic activity (see section III-8).

In order to determine the influence of time of day on the development of a storm, Moos arranged the values of H in the first 24 hours of a storm according to local time and obtained, on the average, the bold curve in Figure 6. In comparison with the ordinary diurnal variation (average of all days, thin line), this curve has a larger amplitude; the effect of the storm is, so to say, to add to the ordinary diurnal variation a simple sine-wave of 24-hour period (the difference-curve in Fig. 6), with a maximum at 6^h and a minimum at about 16^h to 18^h.

The *H*-curve for an individual storm, as a superposition of the curves in Figures 5 and 6, would for various stations near the equator have a different aspect, depending on the local time of the sudden commencement. Figure 7, somewhat idealized, shows the development of one and the same storm at four equatorial stations, at which the storm began at local midnight, sunrise, noon, and sunset (for clearness, the ordinary diurnal variation has been eliminated in these curves). The strongest development occurs at the station for which the storm begins at sunrise and for which the main depression of *H* falls into the evening and night.

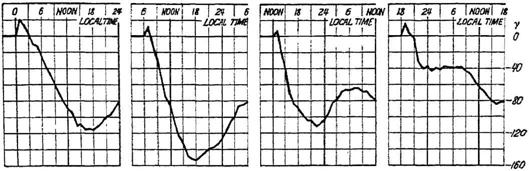


FIG. 7.—Computed (schematic) average curves for horizontal intensity in first 24 hours of same magnetic storm recorded at four equatorial stations, at which the storm began at local midnight, sunrise, noon, or sunset.

Similar calculations for some other observatories, including declination and the vertical component of the Earth's magnetic field, have been made by Chapman, but there is still a great amount of observational material on which computations of this kind may be based.

(2) THE EQUIVALENT CURRENT-SYSTEM FOR AN AVERAGE MAGNETIC STORM

The observations for the average magnetic storm when submitted to spherical harmonic analysis (section IV-1), yield, of course, a primary part produced exterior to the Earth. For illustration, this can be represented as due to a system of electric currents flowing in a spherical sheet surrounding the Earth at some height in the ionosphere. The observed magnetic field can be derived from the lines of current in the usual way; if the right hand, palm downward, is placed on the chart so that the current flows from the wrist to the forefinger, then the horizontal magnetic field is directed at right-angles in the direction of the thumb. The intensity of the field is proportional to the denseness of the current-lines, if these are drawn so that the same current, in amp, flows between every two adjacent lines.

The idealized current-systems for an average storm, viewed from the Sun and the north pole, are as in Figures 18, 20, and 21 of Chapter VII. The system in Figure 18 of Chapter VII is, so to say, the amplified description of the phenomenon given, for the equator, in Figure 5, and, in the same way Figure 20 of Chapter VII corresponds to Figure 6, and Figure 21 of Chapter VII to Figure 7. A large part of the intensity of current is concentrated in the northern and southern zones of maximal auroral frequency, surrounding the poles with radii of about 23°. The higher intensity of the current on the afternoon hemisphere, between noon and midnight, as the combined effect of general and diurnal variations, is also notable. The direction of the horizontal magnetic field is easily derived from the rule given above.

It is to be expected that the influence of season on the general development of a storm should be quite marked, especially in the polar zones having winter or summer. It should be worth while, therefore, to look for it in a sufficiently large amount of observational material. So far, most papers have not considered such seasonal effects but have smoothed them by taking annual averages.

(3) SOLAR STREAMS OF CORPUSCLES

A complete physical theory of the streams of solar corpuscles should account for all the observational evidence—the astrophysical observations as to the origin, and the geophysical observations on terrestrial magnetism, propagation of electromagnetic waves, and aurorae as to the terrestrial effect. There is as yet no trace of the streams during their passage from the Sun to the Earth. Chapman has indicated that it is possible to determine the density and velocity of the stream by comparing the spectrum of the Sun in magnetically quiet and disturbed times. For, during the magnetic disturbance, the Earth is probably enveloped by the stream during many hours, so that the Sun's disk is observed through a more or less long part of the stream moving towards the observer. A travel-time of roughly a day for 150 million km corresponds to an average velocity of over 1,700 km/sec; this would result in a Doppler-shift of the Fraunhofer *K*-line of Ca^+ by about 20 Ångstroms toward the violet, which should be observable if more than one Ca^+ ion were contained in 20 cc. A possible source of high-speed atoms emitted from the Sun has been indicated by Milne [1482]; the process considered by him leads to about 1,600 km/sec velocity. Another theory of the chromosphere and the corona has been given by S. Rosseland [1504].

Since aurora is seen at night, the solar streams cannot be electrically neutral but must contain charged particles, electrons, protons, or ions, in order to yield to the deflection by the Earth's magnetic field. Theory in its simplest form must therefore start with the motion of a singly charged particle in the magnetic field of the Earth. Störmer [839] has devoted many papers to the solution of the differential equations of this problem and has calculated and discussed a large number of orbits. He began this work in order to explain the experiments of Birkeland, who, about 1900, bombarded a magnetized sphere (his model-earth "Terrella") with cathode rays. These experiments have been improved by Brüche [802], who applied self-luminous "thread-rays" of electrons having a velocity of about 200 volts (8,400 km/sec). Under suitable conditions, these rays remain concentrated by the surrounding gas (of 0.001-mm pressure) up to one-meter length. The elegant three-dimensional curves formed by these rays confirm quantitatively Störmer's calculations of the orbits.

(4) STÖRMER'S THEORY

In a homogeneous magnetic field, H, a charged particle (mass, m, charge, e) of the velocity v cm/sec, moving in a plane perpendicular to the lines of force, describes a circle of the radius, ρ, which can be calculated from the condition that the centrifugal force, mv^2/ρ, must equal the deflecting force, evH, exerted by the field, H, on the current, ev, represented by the moving particle. Therefore,

$$H\rho = v(m/e) = s$$

This is called "stiffness" and gives the radius in the magnetic field of unit intensity. For electrons, $e/m = 1.77 \times 10^7$, so that velocities comparable with that of the solar particles, $v = 2{,}000$ km/sec $= 2 \times 10^8$ cm/sec, give $s = 11$ cm. The mass of protons is about 1,850 times greater, and that of calcium ions, 74,000 times. In the magnetic field in the Earth's atmosphere, in latitude 40°, with $H = 0.5$ gauss, and with velocities produced by the average thermal motion, at about 30°C, of $v = 2.7$ or 0.4 km/sec, for protons or calcium ions, the radius is 56 cm and 360 cm, respectively. Since the average thermal velocity, v, is proportional to $\sqrt{T/m}$, with $T =$ absolute temperature, the radii, ρ, are proportional to $\sqrt{mT}$ for singly charged particles. These values of ρ are of great importance for the physics of the ionosphere, because, where they are of the same magnitude or greater than the mean free-path—in the atmosphere, roughly one cm in 100-km height, 1,000 cm in 150-km height—the ions can, between successive collisions, circle round the magnetic lines of force. If the particles move obliquely to the magnetic lines of force, the component of the velocity parallel to the magnetic force is undisturbed, so that the orbit becomes a spiral round a cylinder of radius ρ.

We shall now derive the radius of a particular orbit in the magnetic equator of the Earth. The magnetic moment of the Earth is $M = 8 \times 10^{25}$ CGS. The magnetic field-intensity at the distance, r, from the center, for a point in the equatorial plane, is $H = M/r^3$, that is, near the Earth's surface, with the Earth's radius $r = 6.4 \times 10^8$ cm, $H = 0.3$ gauss. With increasing distance, r, H decreases, so that, for particles of a given stiffness, s, the radius, $\rho = s/H = sr^3/M$, increases more rapidly than the distance, r. Therefore there must exist a circle for which $\rho = r$; its radius, called c, is a characteristic constant in Störmer's theory, and

$$c = \sqrt{M/s}$$

The value of c may be used, instead of s, to characterize all possible orbits of particles of a given velocity, mass, and charge. For calcium ions of $v = 2{,}000$ km/sec, $s = 800{,}000$ cm, and $c = 10^{10}$ cm $= 100{,}000$ km. If, therefore, a calcium ion at any time moves horizontally, with velocity of 2,000 km/sec, at distance $c = 100{,}000$ km from the Earth's center in the equatorial plane, it will continue to circle round the Earth, keeping that velocity and distance.

If a particle of a certain stiffness, s, approaches the Earth from the outside, it cannot get nearer the Earth, in the equatorial plane, than $(\sqrt{2} - 1)\ c = 0.41c$; calcium ions of $v = 2{,}000$ km from the Sun would remain about 40,000 km from the Earth's center or $5a$ (a = radius of the Earth) above the Earth's equator. Toward the Earth's poles, the outer surface of the toroidal space, into which the particles cannot penetrate from the outside, approaches the Earth's surface and intersects it in a circle of angular distance, θ, from the magnetic pole.

$$\sin\theta = \sqrt{2a/c}$$

Because $c = \sqrt{M/s}$, $\sin\theta$ is proportional to the fourth root of s. With $c = 100{,}000$ km, $\theta = 21°$. This would be, under the assumptions made, the outer radius of the polar zone into which solar particles of the stiffness, $s = 800{,}000$, could penetrate into the Earth's atmosphere and cause aurora, by collision with atmospheric particles.

Störmer has, in all his papers, never considered solar particles of such small velocities as we have used for illustration. He considered particles then known from physical experiments, such as cathode rays, or β and α rays. Now, for the small mass of electrons, the stiffness, $s = v(m/e)$, is small, so that $c = \sqrt{M/s}$ becomes very large, and the "forbidden" space allows the electrons to enter the Earth only in the immediate vicinity of the magnetic poles. Even for β rays of radium C, with velocities of over 99 per cent of the velocity of light (or over ten million volts), c, is of the order of one million km, that is, the circular orbit is three times wider than the Moon's orbit, and θ is less than six degrees.

There is an upper limit of s set by the smallest thickness of observed streamers in aurorae, if the thinnest streamers are conceived as produced by particles moving in spirals round the lines of magnetic force. Störmer takes $s = 10{,}000$ cm—corresponding to a spiral of radius $\rho = 20{,}000$ cm, or 200 meters, in the Earth's field of 0.5 gauss in the ionosphere—as an upper limit; this would give $c = 900{,}000$ km, and $\theta = 7°$. Now this latter value is in sharp contrast to the observations. The zone of maximal auroral frequency surrounds the poles with about 23° angular distance, and auroral displays are sometimes seen at much greater distance. One of the strongest displays in history, that of February 4, 1872, was seen at Bombay, at distance 80° from the magnetic pole! Störmer meets this difficulty by taking into account, besides the Earth's magnetic field, the influence of the electric ring-current of radius c, formed by the many particles whose orbits crowd asymptotically near this circle. This current deflects the particles entering the Earth's atmosphere and widens the auroral zone considerably. Brüche's experiments [802] illustrate Störmer's calculations convincingly (Fig. 8).

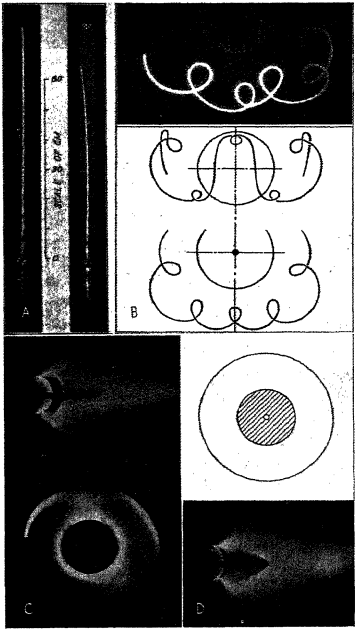


FIG. 8.—Theoretical and experimental results of the Aurora Polaris (*after Brüche*): (*A*) Thread-ray 70 cm in length in a space free from a field (at left) and in the horizontal component of the Earth's field; (*B*) experimental results for computed complicated periodic paths; (*C*) connection between the orbit and the limit of approach from theory (at left) and from experiment; (*D*) action of a ring-current on the electronic torus according to experiment.

(5) ELECTRICALLY NEUTRAL STREAMS OF SOLAR PARTICLES

There is fair qualitative and even quantitative agreement between Störmer's theory, experiments in the laboratory, and auroral observations in so many respects that it must contain a good deal of truth. There remain difficulties. For instance, Vegard points out that the theory could not explain aurorae on the night-side of the winter hemisphere. However, the main objection is more fundamental, namely, the theory does not allow for the mutual influence of the particles. The simplest conception of a homogeneous stream of particles of the same kind—electrons or α rays— had been proved to be untenable, as early as 1911, by A. Schuster [436]. In order to explain an appreciable terrestrial-magnetic effect, the density of the stream must be taken impossibly high—impossible because the mutual electrostatic repulsion of the particles would dissipate the stream long before it reached the Earth. In the space between the Sun and Earth, there is no counterpart to the concentrating effect of the gas in the tube (of 0.001-mm pressure) on Brüche's thread-rays. Furthermore, Störmer takes the velocities of the particles as equal to those occurring in radioactive processes, that is, of the order of the velocity of light; it is, however, rather improbable that radioactive processes to such an extent occur on the Sun's surface.

Lindemann therefore introduced the conception of an electrostatically neutral but ionized stream. Chapman and Ferraro [388] have made it clear that this is the only possible type of solar stream, having the same streaming velocity for the particles of both positive and negative sign. In an extensive paper, they have attacked the difficult problems of the physics of such a stream approaching the Earth. They take its velocity, in keeping with Milne's calculations, between 1,000 and 10,000 km/sec and a lower limit for the density as 10^{-22} gram/cc, or about 50 hydrogen ions or one calcium ion per cc. Such a stream has a lateral extent much greater than the Earth and would travel from the Sun in about a day. In the advancing surface of the stream, which is a highly conducting medium, the magnetic field of the Earth would induce surface-currents and thereby retard the approach. The magnetic effect of these currents in the front-layer, where as much as 10^{13} ions/cc may accumulate, accounts for the initial rise of horizontal intensity. In the main phase of the storm, characterized by the diminution of magnetic horizontal intensity, the stream surrounds the Earth and forms a current-ring, which can persist for some days after the direct supply of solar particles has ceased. This current-ring finally dissipates by escaping surface-charges. Induction in the ionosphere and within the Earth by the variations of the magnetic field and their reaction on the currents in the advancing surface complicates the phenomena. The authors themselves point to many unsatisfactory features in their treatment and expose the theoretical difficulties of the problem. Much further work is needed, from the observational as well as from the theoretical side. The extremely small densities in the stream and the large space required in the laboratory make experiments infeasible.

(6) OTHER THEORIES

Since the actual mechanism of the emission of the solar streams of particles is not yet known, we must still be prepared to meet some day quite another explanation of the relations between terrestrial-magnetic and solar activity. Thus, Maris and Hulburt [824] have presented a theory, according to which magnetic storms and aurorae are caused by sudden blasts of ultraviolet solar light, which excite air-molecules and lift them to great heights, from where they are guided, as ions, along the lines of magnetic force, to the auroral zones. The same ultraviolet flare of the Sun, which is supposed to start a magnetic storm on the Earth, is made responsible for sudden changes in comets, and a statistical survey of great comets and great magnetic storms, it was claimed, showed remarkable coincidences [419]. Even something like the annual recurrences of meteor-showers were thought to be reflected in magnetic storms [417]. It has been shown [804], however, that this ingenious theory fails quite definitely to explain magnetic storms and aurorae and that there are no distinct annual recurrences of magnetic storms [419]. Nevertheless, these ideas have been mentioned here in order to call attention to the interesting arguments brought forward in the controversy. The simultaneous magnetic effect of solar flares is comparatively small and has only recently been detected in connection with the radio fade-outs (see Chapters VII and X).

VI. SOLAR DIURNAL VARIATION, *S*, AND LUNAR DIURNAL VARIATION, *L*

(1) OBSERVATIONS OF SOLAR DIURNAL VARIATION, *S*

Figure 9 shows, for a magnetically quiet month (April, 1928, $u_1 = 34$) and a disturbed month (July, 1928, $u_1 = 107$) the hourly means of horizontal intensity, H, as observed, near the magnetic equator, at the Huancayo (Peru) Magnetic Observatory of the Carnegie Institution of Washington. The hourly means are plotted hour by hour and days are reckoned between local midnights (about 5^h GMT). The international magnetic character-figures, referring to the Greenwich day, are entered in Figure 9. The diurnal variation is very pronounced. Two characteristic features are easily recognized, namely: (*a*) The unequal range of the diurnal variation, even on successive quiet days—April 11–14 and 28–30, 1928—is discussed in section VI-5; (*b*) the depression of the horizontal intensity caused by the magnetic storm of July 7 and 8, 1928, and the gradual recovery, most clearly exhibited in the values at night (see section III-10).

Everywhere on the Earth, direction and intensity of the terrestrial-magnetic force undergo similar more or less regular changes which are repeated every day. This solar diurnal variation, *S*, is a very complex phenomenon. At a given time and locality, the magnetic force, as a vector, can be represented by a straight line, which has the direction of the

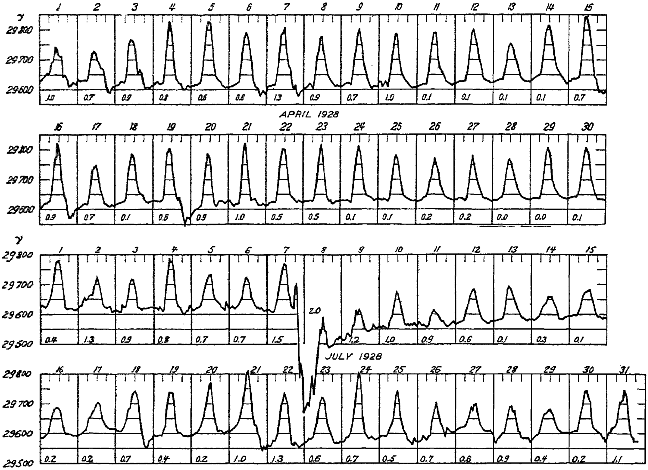


FIG. 9.—Hourly means of horizontal intensity, Huancayo Magnetic Observatory, for quiet month of April, 1928, and for disturbed month of July, 1928, and daily international magnetic character-figures.

force and indicates the magnetic intensity by its length. The end-points of 24 vectors, which all have the same origin, would represent the change of the magnetic force, at hourly intervals, throughout a day. Such models, or stereoscopic diagrams [1260], show that the end of the magnetic vector describes three-dimensional loops, with comparatively rapid changes in daylight and slow changes at night. The aspect of these loops changes systematically with locality (geographic latitude, φ, longitude, λ), with season (astronomical longitude, *h*, of the Sun in the ecliptic), with magnetic activity (international character-figure, *C*), and with solar activity (relative sunspot-number, *R*). The determination of the magnetic diurnal variation, *S*, as a function, S (φ, λ, *h*, *C*, *R*), has been for a long time one of the main subjects of the work done at magnetic observatories. The results are too numerous to be given here in detail.

As usual, the form of the function is determined step by step, keeping four of the variables constant in order to look for the influence of the fifth, for instance, of *R*, etc. For a first survey, it is sufficient to divide the range of the variables, *h*, *C*, *R*, into suitable subdivisions and to form averages of *S* for each group. The seasonal change of *S* is generally expressed by monthly means or, even more condensed, in three averages for 4-month intervals, namely, the equinoxes (March, April, September, October) and for the June- and the December-solstices. As to *C*, quiet days and disturbed days are selected, while the influence of *R* is found by separating years near sunspot-minimum and sunspot-maximum. The pairs of geographical coordinates, φ, λ, for which *S* is accurately known, are those of the magnetic observatories; their unsatisfactory geographical distribution is a great handicap in the interpolation of *S* for other points of the Earth. In order to overcome this difficulty in theoretical work, it is sometimes assumed that *S* is approximately independent of the longitude, λ, so that one observatory covers the simultaneous conditions on the whole parallel. It is then possible to apply spherical harmonic analysis, as described in section IV-1, in order to separate the "interior" and "exterior" parts and to represent them by equivalent current-systems. In this calculation, the "representation" of *S* by the current-systems must not necessarily be taken as the "explanation"; the two schematic current-sheets above and below the Earth's surface are nothing but convenient summaries of the observations.

(2) THEORIES OF THE SOLAR DIURNAL VARIATION, *S*

Charts of these current-systems for magnetically quiet days are reproduced in Figure 10.

The famous "dynamo-theory" of the diurnal magnetic variations of Balfour Stewart, A. Schuster, and others (section II-1) has appeared for over 40 years as the only possible explanation. Variations of temperature and of tidal forces cause the air to perform periodical diurnal oscillations—the atmospheric tides. Near the ground, the shift of air-masses in these tides can be detected by the analysis of long series of hourly readings of the barometer [1261]. In the ionosphere, where the air has an electrical conductivity about 10^{13} times higher than near the ground, the shift of the air across the lines of force of the magnetic field of the Earth induces currents; the magnetic field of these currents is observed at magnetic observatories as diurnal magnetic variation [286].

The exclusive validity of this theory was contested some years ago. It has been pointed out that in high altitudes—above the radio *E*-layer—the conductivity of the air is no longer homogeneous, because the ions and electrons, in the comparatively long intervals between successive collisions, spiral around the magnetic lines of force and do not move readily in the direction of exterior electric and gravitational forces. The physics of a rarefied ionized gas under the action of crossed magnetic, electric, and gravitational fields is the basis of a theory of the ionosphere as well as of the outer atmospheres of the Sun and the stars. Therefore, it has recently been the subject of a great number of papers. Two competitive hypotheses were brought forward and discussed by Ross Gunn [311] and S. Chapman [286], namely, the diamagnetic and the drift-current theories. Both are based on simple conceptions: The electrons and ions spiraling round the lines of magnetic force make the atmosphere diamagnetic; furthermore, under the influence of additional electric or gravitational forces, the spiral motion is superposed by a motion at right-angles to both magnetic and electric forces, that is, by a drift-current (Hall effect). Both diamagnetism and drift-current vary with the change in the ionization from night to day; this seemed to explain qualitatively the solar diurnal magnetic variation, according to both theories, and even quantitatively the drift-currents at least seemed to be of the right order. There are, however, serious difficulties, and T. G. Cowling [55, 56], applying the kinetic theory of diffusion, has shown in detail how the various phenomena, in the isothermal steady state of ionized gases, combine to neutralize one another so that they do not cause a magnetic effect.

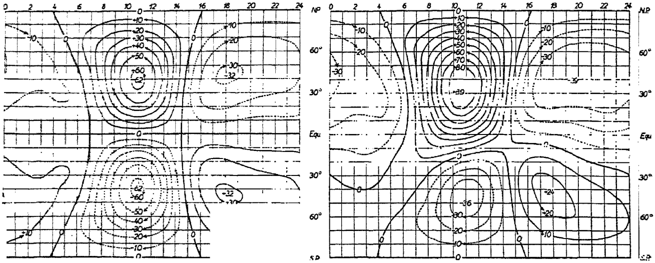


FIG. 10.—World charts of equivalent electric current-systems in ionosphere, representing exterior part of solar diurnal variations on quiet days in sunspot-minimum year 1902 (*after S. Chapman*): Left, currents at time of equinoxes, total main circuits 62,000 amp; right, at time of June solstice, total main circuits 89,000 amp (meridians indicated by local solar time; current of 10,000 amp flows between each two successive lines in direction indicated).

Double refraction of radio waves reflected from the ionosphere allows estimation of the intensity of the magnetic field in the ionosphere. McNish [414] has pointed out that highly accurate measurements of this effect might be used to determine the actual height of those phenomena causing the magnetic diurnal variation.

(3) THE LUNAR DIURNAL VARIATION, *L*

Although thus the alternatives to the old dynamo-theory have lost much of their original attractiveness, there has always remained a stronghold for the dynamo-theory in which its validity has never been seriously doubted, namely, in the explanation of the lunar diurnal magnetic variations, *L*. These may be computed (in actual work the scheme is different) in much the same way as the solar variations, *S*, by introducing a lunar day, reckoned from one lower transit of the Moon to the next. This interval, about 50 minutes longer than a solar day, is divided into 24 lunar hours. The magnetic observations are arranged according to this lunar time and averages for each lunar hour are formed for a large number of lunar days. Because of the regular shift of the lunar day with respect to the solar day, the influence of *S* disappears in the means for complete months and the average lunar variation *L* remains.

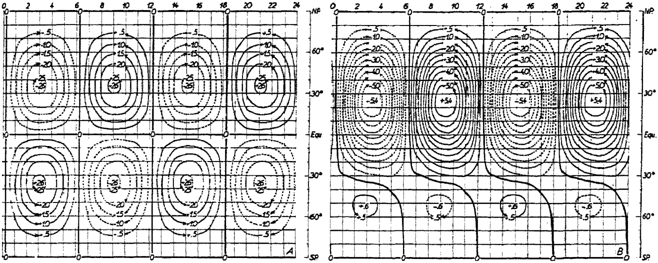


FIG. 11.—World charts of equivalent electric current-systems in ionosphere, representing exterior part of lunar diurnal variations in the average for complete months; (*A*) currents at time of equinoxes, total current of main circuits 2,600 amp; (*B*) at time of June solstice, total current of main circuits 5,400 amp (meridians indicated by local lunar time—12 = upper transit; current of 500 amp flows between each two successive lines in direction indicated).

This *L* is always found to be very simple in character, consisting of sine-waves with two maxima and two minima in the course of a lunar day. This agrees with the tidal origin of the lunar diurnal oscillations of the atmosphere, for which these double waves are even more characteristic than for the tides of the oceans. Spherical harmonic analysis shows that the exterior part of *L*, like that of *S*, is two to three times as large as the interior part [282, 284]. This points to the production of *L* in the ionosphere, in the manner indicated by the dynamo-theory.

Charts of these equivalent currents for *L* are reproduced in Figure 11; they are supposed to flow mainly in the *E*-layer, where the collisions are frequent enough to make the effective electric conductivity independent of direction.

However, this average L is only a part of the phenomenon. Suppose we derive from the observed hourly values of the magnetic elements for magnetically quiet days in all months of April, in a number of years, the average solar variation, S, and subtract this S from the original values. In other words, we subtract the average value for 1^h from each individual value for 1^h, etc. The result will be a series of values freed from the average S. We arrange these according to lunar time; forming the average lunar variation, we should, of course, obtain the same average L as before. Suppose now we keep the days with different phases of the Moon separate; that is, we form phase-groups of lunar days about the new Moon, first quarter, etc. In each group, then, lunar and solar times differ practically by a constant number of hours. At the time of the new Moon, they are practically identical; at the time of the first quarter, the lunar day begins about 6^h solar time, etc. The lunar variation for each separate phase-group is found to be different from the average L; that part of L falling into solar day (from about 6^h to 18^h) is magnified, while the part falling into night is suppressed (Fig. 12).

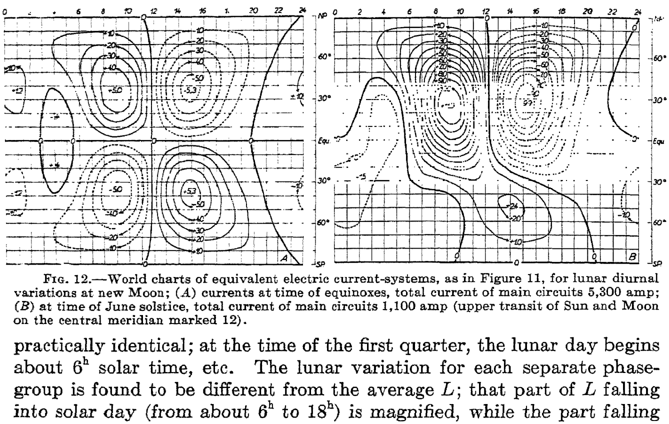


FIG. 12.—World charts of equivalent electric current-systems, as in Figure 11, for lunar diurnal variations at new Moon; (A) currents at time of equinoxes, total current of main circuits 5,300 amp; (B) at time of June solstice, total current of main circuits 1,100 amp (upper transit of Sun and Moon on the central meridian marked 12).

This property of L lends to the lunar diurnal magnetic variation—although the lunar effect is no greater than about one three-thousandth of the total magnetic field—theoretical significance. We know with considerable certainty that the lunar atmospheric oscillation, as indicated in variations of pressure, does not depend on the phase of the Moon, so that the enhancement of L during daylight is an unmistakable sign of the better conductivity, or more intense ionization, of the sunlit ionosphere. It is true that the magnetic S-variation is also more pronounced in day than at night, but since this is also a peculiarity of the diurnal variation of atmospheric temperature and the winds of the solar atmospheric oscillation produced by it, it would have been uncertain to infer, from the magnetic S-variation alone, the diurnal change of conductivity in the ionosphere from night to day.

The derivation of L from the observational material requires a great amount of computational labor, since the order of magnitude of L is less than one-tenth of that of S, so that much more material must be compiled in order to reduce the accidental error. In addition to the five variables mentioned for S, we have, for L, to consider the Moon's phase.

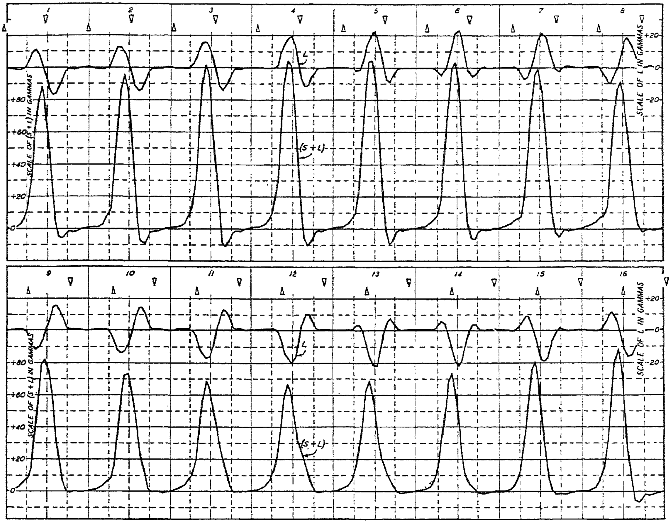


FIG. 13.—Schematic diagram of lunar diurnal variation, L, and of combined solar and lunar diurnal variations, $(S + L)$, in horizontal intensity at Huancayo Magnetic Observatory, representing 16 consecutive calm days during sunspot-minimum, months November to February (upper and lower transits of the Moon indicated at top).

Using the astronomical longitudes, s and h, of the Moon and the Sun, the phase can be represented by $(s - h)$, so that $L = L(\varphi, \lambda, s, h, C, R)$. Chapman [282, 284] pointed out that there seems to be a significant difference in the influence of terrestrial-magnetic activity, C, and of sunspot-number, R, on S and on L, S being more susceptible to changes in R, L more so to changes in C. This would possibly indicate different layers in the ionosphere as origins for S and L. An independent test, based on other observational material, would be of great interest.

The Huancayo Magnetic Observatory of the Carnegie Institution of Washington, which has the largest solar diurnal variation of horizontal intensity, is also outstanding for a large lunar diurnal variation, *L*, especially around the month of December. The records obtained there are therefore extremely valuable for the study of both *S* and *L*. Figure 13 shows, in the same manner as Figure 9, a slightly schematized succession of diurnal variations under the combined influence of Sun and Moon near a sunspot-minimum in December at Huancayo.

(4) THE UTILIZATION OF RESULTS FROM OBSERVATORIES

The foregoing paragraphs referred to the average diurnal variations, *S* and *L*, and the inferences drawn from them. A great part of the work done at magnetic observatories has always been devoted to the rather tedious computations connected with the derivation of *S* and *L*, and it sometimes has been doubted whether this energy could not be more profitably engaged in other researches. To a certain extent this heretic feeling may be justified, namely, in so far as results are often not thoroughly discussed and, above all, are sometimes not so derived that they can be readily combined with results of other observatories. Yet a certain amount of such work—for instance, the computation of *S* on quiet and disturbed days, according to international conventions—is necessary, as preparation for later summaries, and belongs properly to the routine work of observatories. And it cannot be denied that patient work of this kind, repeated year after year along the same lines, has supplied to terrestrial magnetism and geophysics in general a wealth of information.

More than 26,000 hourly values of the magnetic components or elements accrue each year at a single observatory. From a total of roughly 40 observatories with a regular and complete service, the annual output of hourly values is about a million. This large mass of material, shelved in the libraries of a few central meteorological and geophysical organizations, represents the results of a great amount of work. Can we say that the information contained in it is exhausted to any extent and that the use made of it repays the labor spent in the observations?

This question has been asked frequently, and A. Schuster [1280] raised it more than 30 years ago, voicing a vigorous protest against the useless "routine and drudgery," the "collector's fanaticism," the "slavery to continuity," etc., in meteorology and terrestrial magnetism. His appeal ended with the request to stop all observations for five years, in order to concentrate the whole energy and vigor of the observers and computers on the discussion of the results and on the preparation of a better scheme for future observations. These temperamental arguments should be refreshing reading for all geophysicists. However, the reactions of a theoretical physicist against geophysical work of this character must not be too strong, as Hann points out in his comments to Schuster's article. Not all observers now engaged in observatories might be able to engage in a fruitful discussion of data, and any interruption in the patient watch of the large-scale geophysical experiments performed by Sun and Moon will seriously impair the usefulness of the series—especially at a time when astrophysical solar research constantly reveals new details of solar phenomena which call for comparison with geophysical observations and when radio observations on the ionosphere call for simultaneous magnetic records.

In the special case of terrestrial magnetism, there is no doubt that much remains to be done in the way of reduction and utilization of the observations. As to the lunar variations, Chapman [385] has proposed a project for international collaboration and for some kind of central bureau, to be equipped with a set of Hollerith punching, sorting, and tabulating machines; these machines, used by him for similar work with excellent success [1264], may go far in relieving the burden of purely mechanical calculations.

The derivation of such exceedingly small periodic variations from a mass of data with much larger periodic and non-periodic variations has implied the development of new statistical methods for judging the reliability of the results. These methods [270] are characterized by the use of the "harmonic dial" and the "probable ellipse." They will also be of value in those numerous cases where the physical reality of geophysical periodicities is to be tested [361], and their improvement offers a promising field for statistics and the theory of probability.

(5) THE VARIABILITY OF *S*

It has been overlooked for some time that the average diurnal curves, *S*, for different stations and seasons, as well as for different degrees of terrestrial-magnetic or solar activity, do not describe the phenomenon in full. In order to form a complete basis for a theoretical explanation, a description of a geophysical phenomenon must give an account not only of its average value or appearance, but also of its variability.

For instance, take the daily readings of the air-temperature on summer days at noon for a given station. The mere average is no sufficient abstract of the observations if it is not supplemented by information on the frequency, intensity, and succession of hot and cold spells. It would even be incomplete to form average temperatures for days, say with high or low atmospheric pressure, or for clear and dull days, etc., for the temperature may vary considerably from quite different causes which perhaps have been overlooked. The full variability is better represented by the frequency-distribution, giving, for suitably chosen steps, the percentage of days on which the temperature at noon lies in the interval between, say 10° and 11°C, etc. This frequency-distribution is easily calculated from the original observations, without regard to any real or supposed cause.

Our problem is to find a suitable analogon which might represent the full variability of S, as distinguished from the more or less regular changes of S with locality, season, sunspots, or magnetic activity. That part of the variability of S, which cannot as yet be accounted for by the influence of the well-known causes mentioned, might be called, in analogy to other cases in statistics, irregular or fortuitous. Since it is found to be of the same order of magnitude as the regular changes, it deserves to be studied in detail.

Consider, for instance, the records of the vertical component, Z, at Watheroo, Western Australia, on magnetically quiet days ($C = 0.0$ or 0.1), in the southern summer (months, November to February) during the years 1919–20, 1925–26, 1926–27, etc., to 1929–30. These summers were selected for their comparatively high sunspot-activity (average $R = 66$). The Z-variometer traces S for each day, from midnight to midnight, as a continuous curve. The first simplifying step consists in deriving the usual hourly means, so that S, for each quiet day, may be regarded as given by 25 hourly means—25 because we add the first hourly mean of the next day in order to allow for possible non-cyclic changes. N days would yield a set of N combinations of 25 values; in our case, $N = 173$. It is proposed to develop statistical methods for dealing with such a set of data—methods which allow adequately for the strong interdependence of the 25 values for each day.

S. Chapman and J. M. Stagg [288] have opened this field by considering the range, that is, the difference between the highest and the lowest values for the day at various observatories. On individual days this range differs considerably—on the average by 20 to 30 per cent—from the normal range for the season, even on days without any trace of magnetic disturbance ($C = 0.0$ or 0.1). From a statistical analysis of these ranges, regional and world-wide causes affecting S could be distinguished, as well as unexpected relations between the range, the daily mean (that is, the average of the 25 values), and the non-cyclic change (that is, the difference between the first and the twenty-fifth value). The variability of S is illustrated in Figure 9 by the obvious difference of S for the quiet days April 11–14, 24–25, and 28–30.

(6) STATISTICAL METHODS FOR RESEARCH ON THE VARIABILITY OF S

For a more detailed example, we start with the 173 quiet days at Watheroo just mentioned. The average S, for the vertical component Z, is given in the upper heavy curve in Figure 14. By the usual harmonic analysis, this curve is decomposed into several sine-waves of periods of

24, 12, 8, 6, etc., hours. [The harmonic analysis consists in the computation of the amplitudes and phases of the best-fitting sine-waves.] For simplicity, we confine our attention to the first sine-wave, S_1, of the 24-hour period, drawn as a thin line in Figure 14; it has an amplitude of 14 γ and its maximum occurs at $13^{h}4$. This harmonic analysis can be applied not only to the average curve, but also to each of the 173 days, and the 173 sine-waves, S_1, are represented in the "harmonic dial" of Figure 15-*a*. In a dial with 24 "spokes," corresponding to the 24 hours of the day, each day is represented by a dot. The line drawn from the center of the dial (in Fig. 15, this center lies near the upper edge) indicates, by its length, read on a scale in gammas, the amplitude of S_1 and, by its direction, pointing to a time read on the edge of the dial, the occurrence of the maximum of S_1. The mass-center of the 173 dots corresponds to the average sine-wave and is indicated by a heavy dot; around it, the "probable ellipse," containing half the dots, is drawn as a suitable expression for the scattering of the dots. The great variability of S_1 even for such quiet days is surprising. It affects especially the amplitude (the ends of the long axes of the probable ellipse correspond to the amplitudes 8 γ and 20 γ) and also the occurrence of the maximum (the ends of the short axis correspond to $12^{h}.7$ and 14 5).

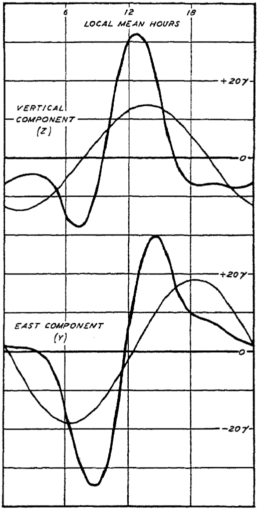


FIG. 14.—Average diurnal variations, Watheroo Magnetic Observatory, 1919–30, on magnetically quiet days (international character-figures 0.0 and 0.1) in southern summer (November to February), for vertical component, Z, and east component, Y, approximating harmonic sine-waves of 24-hour period.

Now we may ask whether these changes of S from day to day, as illustrated by the scattering of the dots in Figure 15-*a*, are confined only to the vertical component, Z, or are they accompanied by similar changes in the solar diurnal variations of the other magnetic components? We look for such an effect in the diurnal variation of the declination, D—the reason why D and not H has been selected at Watheroo is that there the latter does not vary much in the course of a day. The diurnal variation of the declination is approximately proportional to that of the east component, Y, a change of one minute of arc in declination corresponding to 7.3 γ in Y. The average, S, for Y and its 24-hour sine-wave, S_1, are given in the lower curves of Figure 14. S_1 of Y was also computed for each of the 173 days, but the harmonic dial has not been reproduced here. Is there any relation between the corresponding points, or the waves, S_1, in the diagrams for the vertical and the east components? Or if, for an individual day, the 24-hour wave, S_1, in Z has a small or large amplitude, or its maximum occurs early or late, is then S_1 in Y for the same day likely to have a similar characteristic?

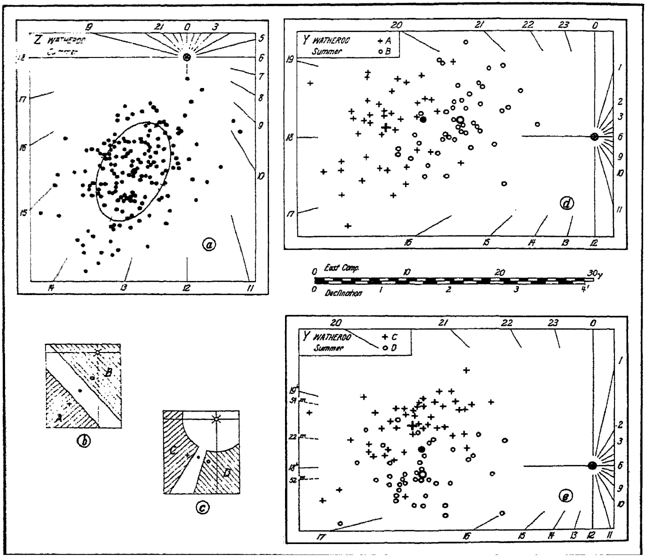


FIG. 15.—Harmonic dials for 24-hour sine-waves in diurnal variation of vertical component, Z, and east component, Y, 173 quiet summer days at Watheroo Magnetic Observatory, showing interrelations between Z and Y.

For a test of this kind, in the harmonic dial for $S_1(Z)$ of Figure 15-*a*, two regions were selected (shaded regions in Fig. 15-*b*), namely, (*a*) days with large amplitudes (region A) and (*b*) days with small amplitudes (region B). The average, $S_1(Z)$, for all days in region A is indicated by a cross and the average for region B by a circle. In Figure 15-*d* the sine-waves, $S_1(Y)$, for days with $S_1(Z)$ in region A are indicated by crosses and the $S_1(Y)$ for days with $S_1(Z)$ in region B by circles; the average, $S_1(Y)$, for each group is indicated by a heavier cross and circle. The result is clear. Days (A) with large amplitudes in Z have also large amplitudes in Y and the same holds for days (B) with small amplitudes.

Another subdivision of the $S_1(Z)$-dial refers to the occurrence of the maximum (Fig. 15-*c*), namely, days on which the maximum occurs more than half an hour later (region C) or earlier (region D) than in the average. The "transformation of the $S_1(Z)$-dial into the $S_1(Y)$-dial" (Fig. 15-*e*) is again quite striking. On the average, the maximum of $S_1(Y)$ occurs on the days in region C more than an hour later than on the days in region D.

If we express the result in terms of the three-dimensional vector-representation of S (section VI-1), we can say that the loop described by the end of the magnetic vector on quiet days in summer at Watheroo changes its form in a way tending to a proportional widening and contracting on individual days and that corresponding points of the loop are sometimes reached an hour or so earlier or later than normal. With reference to the primary diurnal current-systems in the height (Fig. 9), this would point to changes in intensity of the currents as well as considerable shifts of the systems relative to the noon-meridian.

This example will have indicated one of the ways in which a more detailed knowledge of the complex diurnal variation can be obtained. It would be of great interest—though difficult—to find similar variabilities in the lunar diurnal variation.

VII. THE PERMANENT FIELD AND SECULAR VARIATION

(1) The permanent field

We close now the discussion of the exterior magnetic field originating in the ionosphere and turn to the chief interior portions of the permanent field and the secular variation. Some of the reasons for assuming the interior origin of these portions of the magnetic field have been indicated in section IV-2.

The permanent field is represented by maps showing lines of equal values of declination (isogonics), horizontal and vertical intensity (isodynamics), or other magnetic elements. It is often left to the imagination of the reader to visualize, on the basis of these piecemeal data, the actual distribution of the three-dimensional magnetic field-vector. If it is not feasible to draw stereoscopic diagrams, at least a map should be added in which the horizontal part of the vector is indicated by arrows. Such a representation is especially suited for large-scale maps of small areas, in which the magnetic field is measured at a close net of stations.

The reduction of a single field-observation in a magnetic survey to the annual mean is possible by keeping a record of the magnetic variations at a near-by observatory. Experience has shown that within distances of 100 or 200 km the time-changes are practically the same except for times of high magnetic activity or for regions near the magnetic poles. The difference of the magnetic elements between the field-station and the observatory, measured at any moment, is therefore put equal to the quantity desired, namely, the difference of the respective annual means.

There are undisturbed regions on the Earth, in which the magnetic field changes steadily from one place to the other, so that the isodynamics are smooth curves and can be interpolated from the results of relatively few stations, 20 or more km apart. In disturbed regions, caused by local anomalies, the field is more or less irregular and the net of the stations must be closer. All degrees of intensity have been found in local anomalies, from slight disturbances of less than a thousandth of the whole field over salt-domes up to complete reversals of the field-direction over layers of magnetite.

A connection between geology and the magnetic field measured at the surface has been traced in many cases and there is no doubt that all local magnetic anomalies are caused by differences in the magnetization of the underlying geological structure. Prospecting for deposits of ore or other minerals by means of magnetic surveying has become a well-developed branch of applied geophysics [901, 904, 911], with suitable instruments and methods [see Chapter III]. Of course, though a given distribution of magnetized matter in the subsoil causes a well-defined magnetic field at the surface, there is no such "one-way relation" in the other direction. Thus it is not possible to deduce mathematically the unknown distribution from magnetic observations at the surface. The infinite variety of distributions compatible with the observed magnetic field must therefore be narrowed by independent geological considerations, or by other methods of applied geophysics.

Volcanic rocks and layers of magnetite are sometimes found to be strongly magnetized in directions differing widely from the present magnetic field in the neighborhood. It is an open question whether this magnetization is "fossil" and represents the local magnetic field at the geological time at which the rocks were formed or whether it is to be explained otherwise. Besides the geological aspect of the question, it is of interest for pure physics, because these rocks are examples of magnets which have apparently kept their magnetic moments for thousands of years. The fossilized lightning-strokes, the fulgurites, may be mentioned here because of the magnetization in the surrounding rocks.

(2) THE MAIN PART OF THE INTERIOR FIELD

Though, in principle, the local anomalies are easily explained, the situation with respect to the general distribution of the magnetic field over whole continents or the whole planet is rather puzzling. Indeed, no satisfactory theory has been found which accounts for this main part of the Earth's magnetic field.

Magnetic maps of the world are constructed by drawing somewhat idealized isogonics and isodynamics in which the local anomalies are smoothed down. They show two magnetic poles of dip or inclination at which the field-vector is vertical, one at latitude 70°.8 north and longitude 96°.0 east (this pole on the Northern Hemisphere is, physically speaking, a south pole because it attracts the north-seeking end of the compass-needle), the other at latitude 71°.2 south and longitude 150°.8 east. These poles are not antipodal. The straight line joining them, at its nearest point, is 1,140 km (more than one-sixth the Earth's radius) from the center.

On the whole, however, the Earth's field as measured at the surface is rather similar to that of a sphere homogeneously magnetized parallel to the magnetic axis, a diameter of the Earth intersecting the surface at latitude 78°.5 north in longitude 291° east and its antipode. The magnetic moment of the Earth is 8.6×10^{25} gauss/cc, theoretically equivalent to a homogeneous magnetization (moment per cc) of 0.080 gauss. The average magnetization of the Earth would be reached if each cubic meter of the Earth's volume contained a large number of magnets adjusted parallel to the Earth's magnetic axis. The same field would be observed at the surface if all the magnets were not evenly distributed throughout the Earth's volume but were concentrated at the Earth's center or condensed in a concentric spherical shell. Another theoretical possibility would be a distribution of electrical currents, for instance, a current-sheet immediately below the Earth's surface, with currents flowing from east to west and a current-density diminishing from the equatorial value of 0.8 amp across each cm of a meridian, to zero at the end-points of the axis. These are examples for the general thesis that there is an infinite variety of distributions of magnets or electrical currents inside the Earth which would all cause the same magnetic field at the surface.

The magnetic axis is such a fundamental conception that a system of geomagnetic coordinates (latitude and longitude) has been introduced [195], and geomagnetic coordinates have been assigned to each point at the Earth's surface relative to the magnetic axis, much as its geographical coordinates relative to the axis of rotation. Magnetic longitude is reckoned from the great circle connecting the geographic north pole with the northern end of the magnetic axis.

The simplifying assumption of a uniform magnetization is equivalent to that of a strong dipole situated at the Earth's center. If a second approximation is wanted, an eccentric dipole offers itself. It has the same strength and direction as the centered dipole but is shifted by 342 km (toward a surface-point in latitude 6°.5 north and longitude 161°.8 east, in the Pacific) from the geometric center to the magnetic center of the

Earth. The fields of this eccentric dipole and of the regional anomalies with respect to it, have been fully described by Bartels [181].

(3) HYPOTHESES ON THE ORIGIN OF THE MAIN PART OF THE PERMANENT FIELD

The rather small angle of 11°.5 between the Earth's magnetic axis and the axis of rotation is naturally the starting point for numerous hypotheses which tend to explain the Earth's magnetism as an effect of its rotation. The interesting experiments of S. J. Barnett [1259] and others on gyromagnetic effects, in particular on magnetization by rotation, show that, on the basis of experiments in the laboratory, this explanation fails quantitatively by the factor 10^{-10}. Some authors have had recourse to rather desperate hypotheses implying small alterations of the fundamental laws of electrodynamics—too small to be noticed in physical experiments, but accumulating in the dimensions of the Earth. Schlomka [1278], in a survey of these speculations, tries to explain gravitation at the same time and recommends the assumption that the three fundamental forces, at unit-distance between two protons, between two electrons, and between a proton and an electron, stand in the ratio $(1 + \alpha)$ to $(1 + \beta)$ to 1, with α about -10^{-19}, β about $+10^{-19}$, but $\alpha + \beta$ about 10^{-36}.

The validity of all these attempts is unsatisfactory even from the observational standpoint, because only one planet, our Earth, with all its peculiarities, is accessible to magnetic exploration. The only other celestial body with a known magnetic field is the Sun. Angenheister [21], using the equatorial values 55 and 0.3 gauss for the magnetic field of Sun and Earth, discusses the possibility of rotating electrical charges distributed in the volume and on the surface, compensating each other electrostatically, but not with respect to a magnetic effect. However, the Sun seems too unlike the Earth physically to allow relevant comparisons. Hale's observations show a magnetic axis inclined by an angle of only 6° toward the Sun's axis of rotation, but the magnetic field of the Sun decreases much more rapidly within the Sun's atmosphere (at the Sun's equator from 55 gauss in the lowest layers to 10 gauss 150 km higher) than does that of the Earth, where the magnetic field-intensity decreases roughly proportional to the reciprocal third power of the distance from the Earth's center. The theory of this limitation of the Sun's magnetic field, based on the properties of an ionized gas under the action of crossed magnetic, electric, and gravitational fields, is also of interest for phenomena in the Earth's ionosphere, as mentioned in section VI-2.

The simplest assumption always seems to be that of a remnant magnetism, induced in the Earth at some geological time by an exterior, cosmical magnetic field and persisting to our time. However, there is the difficulty that such a permanent magnetization could be confined only to the outermost layers of about 100-km thickness. Below 100-km depth, the temperature is certainly higher than 1,000°C, so that no ferromagnetic material would keep its moment. The faint hope that the critical temperature of magnetization might rise with pressure has not been supported according to the experiments of Adams and Green [179].

(4) Regional anomalies

Spherical harmonic analysis, which yields the separation of the interior and exterior portions of the magnetic field, is also best suited to represent the interior portion as the sum of a series of partial fields according to the order of the spherical harmonic functions. Each of these partial fields can, after Maxwell, be connected with the conception of multipoles. In terrestrial magnetism, however, it is sufficient to distinguish the first terms, equivalent to a dipole (or a homogeneously magnetized sphere or the other equivalents mentioned above), from the sum of all other terms. These first terms determine the direction of the axis and the magnetic moment of the dipole in the best possible manner. More exactly, if F is the observed magnetic field and F_1 is the magnetic field produced by the dipole, spherical harmonic analysis yields F_1, so that the average value of $(F - F_1)^2$, taken over the sphere, is a minimum. The horizontal component of the difference-vector, $(F - F_1)$, is shown in Figure 16. Since the horizontal intensity, H_0, near the equator is 0.3 gauss, the comparison between the lengths of the arrows and the scale indicated on the map shows that $(F - F_1)$ reaches values from $(H_0/2)$ to $(H_0/3)$.

These regional anomalies can be roughly arranged in four large areas in which the arrows tend to converge towards a center, namely, in Central Asia, a line in the Pacific and in North America, a region south of Africa, and a region south of South America.

Another way of illustrating the deviation of the actual field, F, from the idealized field, F_1, is the following: A world-map showing isogonics according to F_1 would show western declination on that half the Earth containing Europe and bounded by the meridians 69° west and 111° east and eastern declination on the other half; the meridians mentioned are those on which the magnetic axis ends, and they would show zero declination. A glance at the actual map of isogonics is sufficient to recognize the difference from this ideal distribution, especially the remarkable region of abnormal eastern declination in Europe and Western Asia.

(5) Secular variation

The distribution of the secular variation over the globe is in no way an imitation of that of the regional anomalies (section VII-4); however, it has

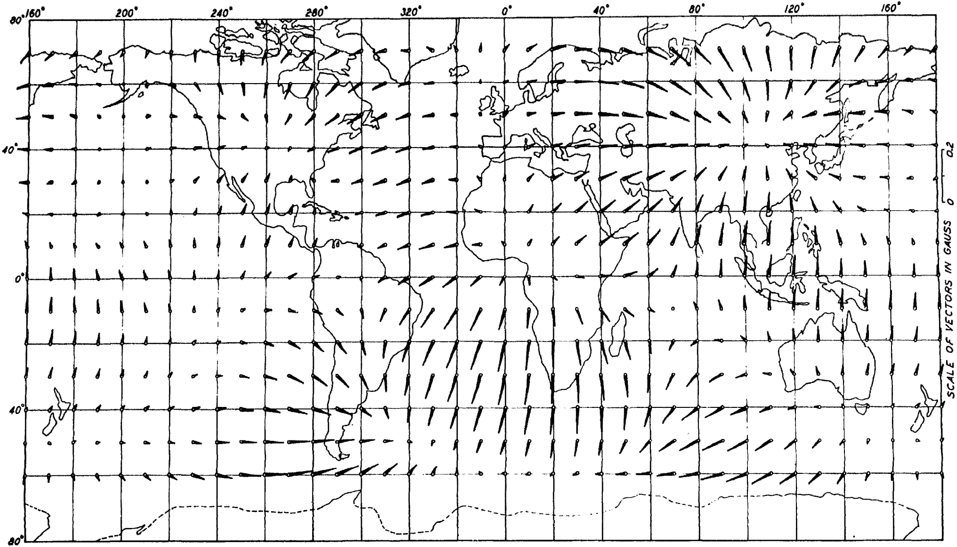


FIG. 16.—Horizontal components of regional anomalies, indicated by differences between Earth's actual magnetic field and approximating field of a hom geneously magnetized sphere.

the same type in so far as large areas of the size of continents have a fairly uniform change from year to year. Local anomalies of geological origin, which are conspicuous in the permanent field, hardly appear in the secular variation; there are instances of observatories in highly abnormal regions at which the secular variation fits well with the values derived in the undisturbed neighborhood. Therefore, it is sufficient to watch the secular variation at a rather wide net of stations, several hundred km apart.

N. H. Heck [351] has published a series of charts showing secular variation in the United States; this series gives a clear impression of the phenomenon during the past century.

In several regions of about one one-hundredth up to one-tenth of the Earth's surface, the secular variation is a simple function of the geographic coordinates. In all Western and Central Europe, for instance, the geographical distribution of the secular variation for each magnetic element can be approximately expressed by a linear formula containing latitude and longitude. But these separate regions, in which the secular variation shows a certain dominant feature, fail to merge into a simple distribution if the whole Earth is considered. There is, in the secular variation, no counterpart to the conspicuous dipole field (homogeneously magnetized sphere) which lends to the permanent field such an appearance of a planetary phenomenon. This is confirmed by spherical harmonic analysis of the secular variation, in that the predominance of the first terms over the remainder is missing! There is therefore not the slightest support for the assumption that the secular variation consists mainly in an increase or decrease of the Earth's magnetic moment or in a systematic shift of its magnetic axis.

For intervals of the order of centuries, the secular variation at a given place progresses in one direction. Since the field-intensity could not be measured before the nineteenth century, we must rely on observations of the field-direction and quote declination at London. The change in declination of 35° from 1600–1800 can be conceived as the gradual superposition of a magnetic field of at least 0.10 gauss, which is comparable with the horizontal intensity of 0.18 gauss today. Even within the comparatively short time from 1891–1931, the magnetic field-vector as measured in 1891 near Berlin has altered by a vectorial amount of over four per cent—mainly by a rapid decrease of declination from 10°.8 to 5°.5 west. This accumulative tendency of secular variation, in conjunction with its regional character, seems to be decisive for all theories of the permanent field because it makes that part of the permanent field which is really a stable planetary phenomenon appear much smaller than is generally assumed.

The geographical distribution of secular variation is best represented in a stereoscopic chart [1260]. It is hard to find in it some simple relation to the distribution of oceans and continents. The region of apparent increasing attraction at the west coast of South America may be of interest in connection with Wegener's hypothesis of the drift of continents. Ross Gunn [1266] and others [350] have indicated an attractive hypothesis, equivalent to the dynamo-theory of diurnal magnetic variations, namely, that, in the course of slow geological processes (perhaps isostatic readjustments), deep layers in the Earth's crust of high electric conductivity might rise or sink and thereby, by induction of the Earth's permanent field, produce large electric currents, the effects of which we observe as secular variation. According to Vening Meinesz [1274], the results of gravimetric observations may be interpreted as the result of large-scale convective motion in the Earth's substratum below the outer crust; this could be the mechanical basis for an application of the dynamo-theory. However, the conductivity required for the subcrustal matter appears too large.

(6) Need for new observational material

The descriptions of the permanent field and of the secular variation as outlined here are subject to modification in quantitative respects by new observational material. The scantiness of the data from the polar regions, for instance, affects the results of spherical harmonic analysis and the conclusions regarding the interior and exterior portions of the Earth's field. In this respect, Sir Frank Dyson and H. Furner [189] have demonstrated that the small external portion and the spurious non-potential portion of the permanent field are quite different if the observations of the vertical intensity between the circles of latitude 60° and 80° are or are not included in the analysis.

In the observations of the magnetic field at single stations, the accuracy attained is quite sufficient for the derivation of the permanent field, and it might seem useless to diminish the instrumental error any further. But the value of instrumental improvements lies in the determination of the secular variation. Suppose a "repeat-station" at which the horizontal intensity, H, is measured as 25,300 γ at one time, and 25,600 γ after ten years. Then the average secular variation is $300/10 = 30\ \gamma$ per year. If this value is required to have a mean error of less than ten per cent, this would imply that each of the two observations must have a mean error less than about 20 γ—less than one-thousandth of H. This mean error would include the uncertainty in the reduction of each single observation to the respective annual mean, because of diurnal variation and the effect of magnetic activity. In remote regions this accuracy is hardly obtained at stations on land and certainly not in determinations at sea.

The cruises of the *Galilee* and the non-magnetic *Carnegie* during 1905–29 have brought the first accurate information about the permanent field on the open oceans and also, at intersections of the successive cruises, values for the secular variation. Since the loss of the *Carnegie* no suitable vessel has been available to continue the work. However the non-magnetic vessel *Research* of the British Admiralty, launched April 4, 1939, will shortly resume the magnetic survey of the oceans; she will reap, in the determination of the secular variation, the fruit of the *Carnegie's* pioneer work (see Chapter I).

(7) OBSERVATIONS AT SEA

Since more than two-thirds of the Earth's surface is covered with water, it is of the greatest importance to consider how the survey-work of the non-magnetic vessels can be resumed with less expensive means. The motion of the ship causes the main difficulty in magnetic measurements at sea. A vessel much smaller than the *Carnegie* (which displaced 568 tons) would have so much motion that probably no very accurate magnetic results could be obtained. Not only the accidental mean error, or standard deviation (on the *Carnegie* about 0°.05 to 0°.1 in declination and inclination, and 50 γ or more in horizontal intensity) would be increased in magnetic observations under these conditions, but there is danger of one-sided errors, so-called "dynamic deviations," the theory of which is still obscure because the amplitudes of the swinging compass-needle are too large to allow application of the well-developed theory of small oscillations [1275]. This consideration precludes the use of rafts, towed by an ordinary ship at such a distance that the effect of the ship's iron is not noticeable.

Possibly a better suggestion is to enclose instruments of the earth-inductor type, or of another electromagnetic type, in a buoy of vanishing buoyancy let down to float in the comparatively quiet regions 100 meters or more below the surface and remote from the iron of the ship, with suitably insulated cables to make the electrical readings on board. The readings might be taken while the ropes connecting ship and buoy are let free. Considering the accuracy desired, the design of such a buoy or some equivalent instrument will require much thought and design. The continuation of the magnetic survey at sea and the further improvement of instruments for use on land are most urgent problems in the observational technique of terrestrial magnetism.

VIII. OBSERVATIONS OF MAGNETIC FLUCTUATIONS BETWEEN 10,000 AND ONE CYCLE PER SECOND

It has been mentioned that the various terrestrial-magnetic phenomena are most clearly expressed in appropriate time-averages. In this respect it must be kept in mind that the usual terrestrial-magnetic instruments contain magnets which have periods of free oscillation of the order of some seconds; they therefore indicate only slow changes in intensity and direction of the magnetic field, while quick changes occurring within fractions of a second are suppressed. Now the usual instruments record rather rarely, but then quite distinctly, "micropulsations" of a surprising regularity, in trains of oscillations with periods of the order of some sec up to about a minute [405, 431]. They seem to be the effects of rather local electric currents in the ionosphere. It would be of interest to explore the higher frequencies—several oscillations per sec and higher. These are more distinctly obtained by recording, instead of (for instance) vertical intensity, Z, the time-changes, dZ/dt, as indicated by the electric current induced in a horizontal loop of wire. Such loops have been used previously in the First Polar Year (1882–83), and others are now installed at some observatories (Eskdalemuir and Watheroo). They have shown their value by indicating the exact times of the commencements of magnetic storms, and the regular oscillations occasionally recorded by the galvanometer have received some comment. However, it cannot be said that we have anything like a systematic survey of natural magnetic oscillations having frequencies between about 10,000 cycles and one cycle per sec, that is, between the longest radio waves and the magnetic oscillations recorded by instruments at observatories.

The ingenious instruments of Adolf Schmidt and La Cour recording a full day's variations of three magnetic elements on an open time-scale on one sheet of photographic paper do not differ, as to the essential magnetic system, from the usual magnetographs (see Chapter II).

IX. EARTH-CURRENTS AND AIR-EARTH CURRENTS

(1) Vertical earth-currents

Of the various types of earth-currents flowing in the Earth's crust, those of electrochemical origin are most easily explained. Certain metallic ore-bodies, corroding at the upper surface under the action of the atmospheric oxygen, form, together with the ground-water, large electric cells. The potential-differences, as measured at the surface of the soil, are used in geophysical prospecting for locating these ores.

More problematic are the vertical earth-currents, as O. H. Gish [1393] has pointed out. If an isolated wire is stretched along a mountainside and the two ends are connected, by electrodes, with the soil, an electric current is found to flow uphill in the wire, corresponding to potential-differences of the order of one volt per km. Gish suggests that possibly the acidity of the soil (the hydrogen-ion concentration of soil science) or some allied property varies systematically with altitude. He compares a mountainpeak with a battery through which a current does not flow unless the circuit is closed by an external conductor (see Chapter VI).

(2) AIR-EARTH CURRENTS

These vertical earth-currents have some interest because of their apparent bearing on a controversy regarding the vertical electric currents flowing in the lower atmosphere. The direct measurements of such currents, by the methods of atmospheric electricity, give a current-density of about 3×10^{-16} amp/cm², flowing downward into the negatively charged Earth; this value is found in quiet weather. During squalls and thunder-storms, the current flows upward or downward, and the point-discharges over grass can furnish current-densities 10^5 times as high, but only during short intervals, so that the average current-density is certainly of the order measured in fine weather. In principle, there is the possibility of checking these electric measurements by means of a magnetic survey. Thus the line-integral of the horizontal components of the magnetic field, measured along the contours of a sufficiently large horizontal area with the average vertical current-density, i, is equal to $4\pi i$. Such calculations, made by Adolf Schmidt [1279] and L. A. Bauer [1262], yield values for i of the order 3×10^{-11} amp/cm², which is 10^5 times greater than the result of atmospheric-electric measurements.

Is it necessary to regard the magnetic evidence for currents of this order as conclusive and to consider a corresponding non-potential field in the permanent magnetic field? The simplest demonstration of the magnetic effect of these currents has been given by W. J. Peters [197]. On a world-chart of isogonics he constructed paths, starting on the Greenwich meridian, for instance, in latitude 50° north and running eastward everywhere at right-angles to the direction of the compass-needle. If there were no average vertical currents in the region of which this path is the contour, the end-point of this circumnavigation, yielding a vanishing line-integral, should coincide with the starting point. Five paths actually constructed for the Northern Hemisphere ended, on the average, about 34 km south from their respective starting points, and five paths for the Southern Hemisphere ended 96 km north. This lack of closure, taking it as physically significant, could be accounted for either by currents of the order mentioned or by systematic average errors in magnetic declination as plotted on the charts, of 3′ east in the Northern, 9′ west in the Southern Hemisphere.

If the vertical currents were of the order measured in atmospheric electricity, the paths should close within a few meters. This could be hardly attained in such constructions. And while the results of Bauer and Peters tend to show some kind of systematic zonal arrangements of the currents—outward at the poles, downward at the equator—the calculations of Dyson and Furner [189], who divided the tropical zone, between 30° north and south, into six quadrangles, each covering one-twelfth of the Earth's surface, demonstrate that the computed vertical currents are quite irregular, without any relation to the distribution of land and sea or other geophysical phenomena. On the whole, these results can be interpreted to the effect that the actual vertical electric currents are too weak to be detected by magnetic surveys and that, therefore, the currents deduced from magnetic observations are spurious.

Sir Arthur Schuster proposed to settle the question definitely by a detailed magnetic survey of a small area. This would be a rather costly undertaking because of the necessary accuracy which would be at the limit for the instruments now used. S. Chapman and A. T. Price [287] have calculated line-integrals of the diurnal magnetic variations and regard the evidence for the existence of a potential as adequate. The author supports their conclusion that the computed values for the currents are within the limits of the observational errors and that the onus of proof rests with those who may hold the opposite opinion.

(3) RELATIONS BETWEEN TERRESTRIAL MAGNETISM AND EARTH-CURRENTS [SEE CHAPTER VI]

The main result of earth-current variations has been their close relation to terrestrial magnetism, times of high activity and of aurorae at polar stations coinciding in the two phenomena. Therefore, it is clear that the 11-year cycle and the 27-day recurrence-interval in magnetic activity are reflected in the earth-current records. The diurnal variations of the two phenomena are also interrelated, since W. J. Rooney [886 and Chapter VI] has found characteristic differences in the diurnal variation of earth-current potentials on magnetically disturbed and magnetically calm days. Even the variability of the solar diurnal magnetic variation on calm days (section VI-5) has been traced in parallel changes of the earth-current variations, at least in a significant case [1388], and studies of the lunar diurnal variation in earth-currents reveal further relations.

The detailed physical explanation of these interrelations between terrestrial magnetism and earth-currents is, however, very unsatisfactory. The primitive attempts to interpret the variations of the magnetic field, as observed at a certain station, as induction-effects of the variations of the earth-current observed at the same locality, or vice versa, have failed because the variations over a sufficiently large area must be considered. S. Chapman and T. T. Whitehead [864], using spherical harmonic analysis of the diurnal variations, have obtained some qualitative agreement between the earth-currents recorded at the Ebro Observatory, Tortosa, Spain, and the theoretical induction-effect caused by the diurnal magnetic variation.

But the agreement was confined to the aspects of the observed and calculated diurnal curves, while the scales differed by a factor of 5 or 6.

In this respect, Gish [1393] has mentioned an even more fundamental difficulty, often overlooked, and showed that the relation between the electric current in the Earth and the current, or the potential-difference, measured between two electrodes connected by wires, is not at all easily interpreted. The stratification of the subsoil with respect to conductivity, the distribution of land and sea, with their enormous difference in conductivity, and the skin-effect, shielding the Earth's interior against the rapid magnetic variations, introduce additional uncertainty. That the local geological conditions affect the earth-current observations more than the terrestrial-magnetic records seems to be indicated by the property of most variations of the earth-current potential-gradient, namely, that all time-changes affect the numerical value of the gradient more than its direction. This makes the scarcity of observatories recording earth-currents even more serious.

It is doubtful whether the study of earth-currents will help materially in the explanation of that part of the magnetic variations which is due to currents induced in the Earth by the primary magnetic variations of ionospheric origin. In fact, the extreme opinion has sometimes been held that horizontal earth-currents as usually observed are secondary phenomena, the details of which are complicated and perhaps do not warrant much attention. However, they are the only accessible manifestations of the electric phenomena in the Earth's crust and therefore should be studied.

CHAPTER IX

RADIO EXPLORATION OF THE EARTH'S OUTER ATMOSPHERE

L. V. Berkner

Department of Terrestrial Magnetism, Carnegie Institution of Washington

I. INTRODUCTION

A highly developed technique in a particular field of research often proves a barrier to the most wide-spread utility of information so obtained. Often this barrier can be removed by a simple consideration of the background and of the basic ideas underlying the investigation. In preparing this Chapter this has been borne in mind in an attempt to lay a groundwork for those who may be unacquainted with the rapid developments in radio exploration of the Earth's outer atmosphere. It is hoped that it may aid in the approach to more detailed discussion and application of the data.

Suppose we briefly review the nature and application of such studies. With the modern technique there are observed effectively virtual heights for each value of ion-density through the outer atmosphere. As indicated later, these appear on a photographic trace as a graph of ion-density versus virtual height.* Such graphs are obtained at periodic intervals (usually several each hour). From them is obtained a comprehensive, quantitative picture of the behavior of the ionized regions of the outer atmosphere, diurnally, seasonally, over longer periods, and during unusual changes. This is the experimental basis upon which can be laid theories of formation of these ionized regions and of the geographical rôle which they play.

In making these measurements we are working in the very regions and with the same ion-formations which give rise to magnetic changes, to auroral displays, and to induced earth-current effects. These ion-layers turn back the transmitted radio waves so that communication over great distances is possible. Quantitative prediction of performance of radio waves over long paths is becoming possible as knowledge of behavior of the reflecting layers is obtained. Because production of ions in these regions arises principally from radiation emanating from the Sun, we have a measure of solar radiation producing them. With the rise of the present cycle of solar activity, ion-density of all regions has increased—in the highest or the so-called F_2-region—by more than 400 per cent. Here, indeed, is a sensitive measure of solar activity which permits numerical evaluation of results, independent of the observer's judgment. There is not space to enumerate all the applications but one should not forget the ionosphere as a low-pressure laboratory, unbounded by side walls, in which physical and photochemical processes associated with ion-production can be studied.

---

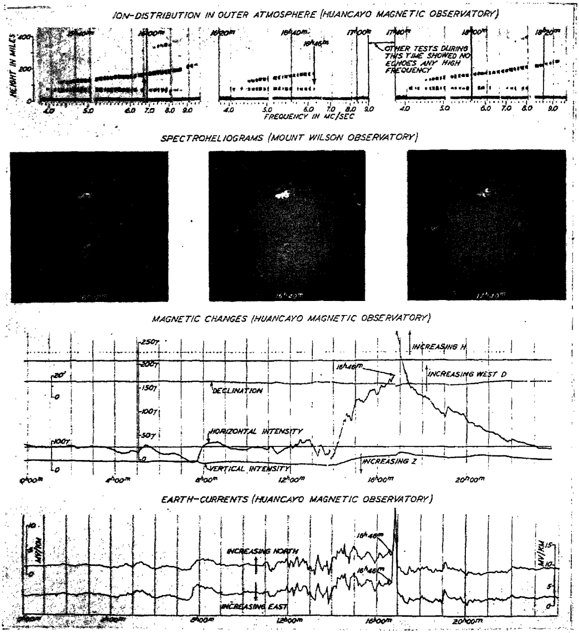
* There is good reason to believe that the virtual height is not greatly different from the actual height over most of the record, limits of the exceptions being uniquely defined by the character of the record itself.

The outer atmosphere of the Earth provides a bond within which many phenomena on the Sun are translated to resultant effects on the Earth. One of the most convincing demonstrations of this is the recent discovery of the radio fade-out effect. Dellinger and Jouaust found independently, late in 1935, that radio fade-outs of wide-spread influence occur on the sunlit hemisphere of the Earth. In a search for their cause, Dellinger found that sometimes there occurred a coincident magnetic fluctuation and was led to suspect a common solar origin of these effects—a suspicion which was soon adequately confirmed. A number of examples of the effect in all its phases are to be found in the records of the Huancayo Magnetic Observatory, which, located at the magnetic equator in the Peruvian Andes, records changes in the Earth's magnetic field, earth-currents, ion-distribution of the ionosphere, and other related geophysical effects. On April 8, 1936, Torreson, Scott, and Stanton at Huancayo, unaware of Dellinger's results, observed all the principal phenomena associated with a radio fade-out. (See Fig. 1 for which the spectroheliograms were furnished by the Mt. Wilson Observatory of the Carnegie Institution of Washington because photographic methods are not available with the spectrohelioscope at Huancayo; at this time a special study of the chromospheric eruptions was being made at Mt. Wilson as a consequence of Dellinger's announcement.) Coincident with the commencement of the solar eruption, radio echoes from the ionosphere faded out on all frequencies, reappearing only after the eruption had subsided. At the same time, the Earth's magnetic field changed suddenly, with correspondingly induced potentials in the Earth.

Here, then, we have examples of effects observed on the Sun and simultaneously on the sunlit hemisphere of the Earth—a brilliant sunspot-eruption accompanied by a cessation of high-frequency radio communication and violent fluctuations in the Earth's magnetic field and in currents flowing in the Earth's crust. The question arises: How is it possible for an eruption on the Sun to have such wide-spread effects on the Earth? What is the physical mechanism by which such an eruption can interrupt radio communication, can change the force and direction of the Earth's magnetic field, and can affect currents flowing in the Earth?

The example cited describes only one of the numerous relationships which we know to exist between solar changes and terrestrial effects.

It was realized as early as 1843 by Schwabe of Dessau that the number of sunspots varied systematically over a period of about 11 years, that is, the time-interval between the occurrence of minimum numbers of sunspots. As the number of sunspots varies, the magnitude of fluctuation and frequency of disturbance of the Earth's magnetism change similarly,


ION-DISTRIBUTION IN OUTER ATMOSPHERE (HUANCAYO MAGNETIC OBSERVATORY)

SPECTROHELIOGRAMS (MOUNT WILSON OBSERVATORY)

MAGNETIC CHANGES (HUANCAYO MAGNETIC OBSERVATORY)

EARTH-CURRENTS (HUANCAYO MAGNETIC OBSERVATORY)

FIG. 1.—Magnetic, radio, and earth-current disturbances associated with brilliant solar eruption, April 8, 1936 (GMT throughout).

so that magnetic activity is greater when sunspots are more numerous. The auroras and earth-currents are related in a like manner to solar and magnetic activity. Then there is the tendency for 27-day recurrence. If a magnetic disturbance or a severe radio disturbance occurs today, it is probable that one will occur 27 days from today, and perhaps again 54 days from today. Now this period of 27 days is the average time required

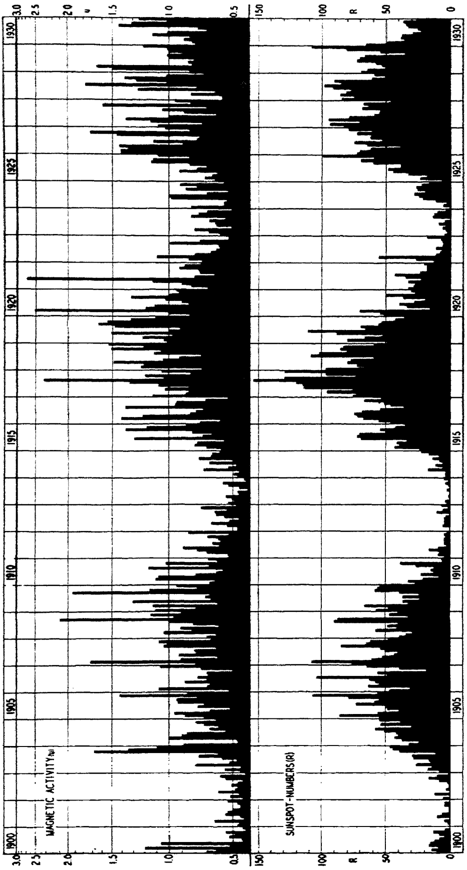


FIG. 2.—Monthly means of magnetic activity and sunspot-numbers, 1900–30.

for a sunspot to rotate with the Sun from a position toward the Earth, around to a position toward the Earth again. J. Bartels, recently discussing these effects in detail, has shown how such correlations can best be derived [972]. Figures 2 and 3 demonstrating these relationships are taken from his work (see also Fig. 43 of Chapter I).

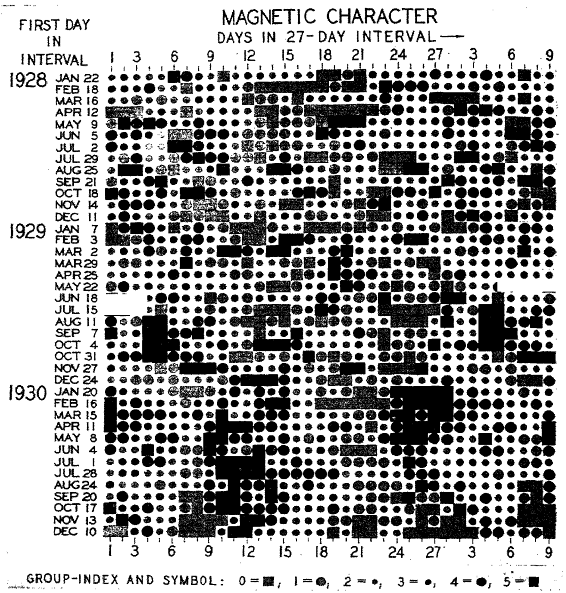


FIG. 3.—27-day recurrence-tendency.

All these facts show that not only are magnetic activity, radio transmission, auroras, earth-currents, and similar phenomena closely related, but they are also related definitely to events, some visible and some invisible, which occur on the Sun. We must again repeat the question: What are the physical mechanisms by which events on the Sun have such wide-spread influence on the Earth? What is the nature of these emanations from the Sun which cause these terrestrial reactions? Such questions have been troubling investigators since the inception of studies in meteorology and terrestrial magnetism.

II. HISTORICAL BACKGROUND

A start toward the proper solution was made with the masterly mathematical developments of Gauss just about a century ago when he showed how it was possible to separate the magnetic field of the Earth into two parts—one part originating inside the Earth and the other originating in regions external to the Earth's crust. Not enough magnetic data from widely separated locations were available at that early date to permit him to conduct the actual operation for the variations of the Earth's field. His work did, however, greatly stimulate the construction of magnetic observatories which made such a separation of the magnetic variation-field into its internal and external sources eventually possible.

In 1882, Balfour Stewart [50] published the first suggestion that daily fluctuations in the Earth's magnetism must arise from an electrical condition in the Earth's outer atmosphere. He proposed that this electrified outer atmosphere formed the bond between effects on the Sun and the related geophysical changes which were observed on the Earth.

It is worth while to read from Balfour Stewart's conclusions. He says:

> We are thus driven by the method of exhaustions to look to the upper regions of the atmosphere as the most probable seat of the solar influence in producing diurnal magnetic changes, and it need only be said that the only conceivable magnetic cause capable of operating in such regions must be an electrical current. Now we know from our study of the aurora that there are such currents in these regions. . . . A good deal has been said about the difficulty of imagining a daily set of currents to be generated in the regions of such imperfect conductivity but . . . there seems ground for believing that their conductivity may be much greater than has heretofore been supposed.

Balfour Stewart thought, however, that the electrical conditions affecting the Earth's magnetism must exist at about the upper cloud-level, which we now know to be much too low. Sir Arthur Schuster succeeded Balfour Stewart as Professor of Physics at Manchester in 1888, and a year later he published the results of a mathematical analysis conducted along the lines which had been earlier suggested by Gauss [327]. In this, he conclusively proved that certain variations in the Earth's magnetic field must originate in a region exterior to the Earth's crust.

The conclusions of Stewart and Schuster found only limited circulation outside their field, so that in 1900, when Marconi made his first transmission of radio waves across the Atlantic, engineers were at a loss to know how radio waves were bent around the Earth. It appeared that, as radio waves were of the same nature as light, they should travel off into space at a tangent to the Earth. In 1902, Professor A. E. Kennelly [1047] of Harvard and O. Heaviside [1034], an English engineer, both apparently unaware of the earlier deductions from terrestrial magnetism, independently proposed that an electrically conducting region must exist in the Earth's outer atmosphere which reflects the radio waves back to the Earth. This is the well-known "Kennelly-Heaviside layer" designated by the more general name "ionosphere." Professor Kennelly tentatively assigned a height of about 80 km (50 miles) to this region, a height since shown to be very nearly correct [see Fig. 4].

The period following saw much activity in theoretical investigation of the manner in which waves could be propagated in such a medium, of how such ionized regions could affect the Earth's magnetism, and of the way in which the regions themselves would be formed. The names of Eccles [1005, 1173], Larmor [1055], Appleton [940, 945, 952, 1173], Nichols and Schelleng [1074], Breit and Tuve [991, 992], Taylor and Hulburt [1104], Pedersen [1077], and Baker and Green [971] all figure prominently in the earlier development of the theory of radio-wave propagation, their work being based essentially upon Lorentz's classical "Theory of electrons" [1057]. Meanwhile basic ideas concerning layer-formation in the outer atmosphere were developed by Chapman [283, 999] and by Hulburt [1038, 1039]. Thus the outlines of the problem were gradually brought into clear relief.

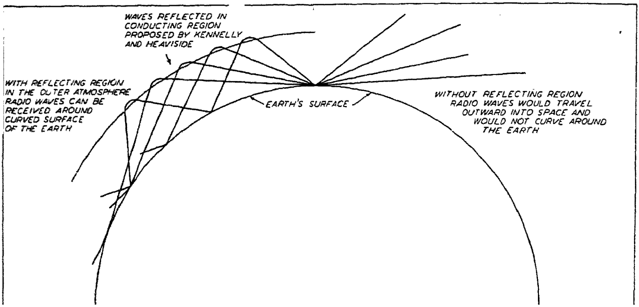

WAVES REFLECTED IN CONDUCTING REGION PROPOSED BY KENNELLY AND HEAVISIDE
WITH REFLECTING REGION IN THE OUTER ATMOSPHERE RADIO WAVES CAN BE RECEIVED AROUND CURVED SURFACE OF THE EARTH
EARTH'S SURFACE
WITHOUT REFLECTING REGION RADIO WAVES WOULD TRAVEL OUTWARD INTO SPACE AND WOULD NOT CURVE AROUND THE EARTH

FIG. 4.—Early radio evidence for an electrically conducting region in the outer atmosphere.

Here, then, were two independent phenomena—terrestrial magnetism and radio-wave transmission—each of which required the existence of an electrically conducting region in the upper atmosphere to explain its effects. It now required only the tools to prove directly the existence of such an electrified region in the outer atmosphere and to show its characteristics. This problem was undertaken almost simultaneously by Appleton and Barnett [950] in England, by Breit and Tuve [992] of the Department of Terrestrial Magnetism in Washington, and by Taylor and Hulburt [1104] of the United States Naval Research Laboratory in Bellevue. Each group used a different method.

III. THE BREIT-TUVE EXPERIMENT

The method of Breit and Tuve was the most simple and direct and now almost universally forms the basis for modern methods of ionospheric measurement. They reasoned that if the ionosphere were at about 100 km (60 miles) in height, it should take about six ten-thousandths sec for a radio wave, propagated at the velocity of light, to travel up to the ionosphere, to be reflected, and to return to the Earth. Then, if a pulse of radio waves of a much shorter duration, perhaps one or two ten-thousandths sec, were transmitted upward, the reflection should be returned and observed quite distinctly a few ten-thousandths sec after the transmission had been completed. The experiment was conducted between the Department of Terrestrial Magnetism and the Naval Research Laboratory. Not only were definite reflections observed from the ionosphere, but they were of such character as to indicate that a complex electrical structure must exist.

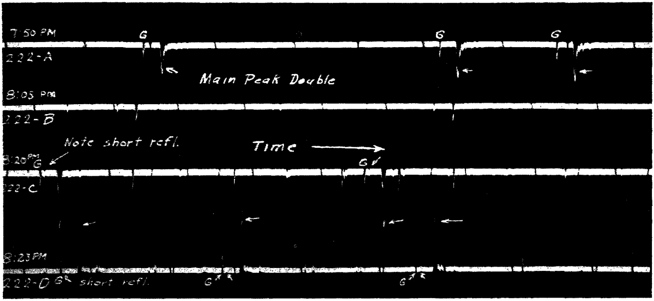


FIG. 5.—Original oscillograms made by Breit and Tuve for ionospheric measurement at Department of Terrestrial Magnetism, Carnegie Institution of Washington, October 18, 1928 (*G* indicates transmitted pulses while pulses following are reflections; time-marks across base-line are 0.01 sec apart).

This, then, forms the basic experiment around which the structure of our modern studies of the ionosphere has been erected. It establishes definitely that the outer atmosphere must contain electrically charged particles in large numbers, which is exactly the condition required to explain the effects of terrestrial magnetism and radio transmission.

With the reality of the ionosphere established, the question arises: What are the mechanisms within this medium through which the Sun influences terrestrial magnetism and radio transmission and generates the other effects which we have mentioned? The answer to this question is the objective of modern research into the electrical state of the upper atmosphere. To obtain the answer it is necessary that we learn how these electrically charged particles or ions are distributed through the outer atmosphere. What is the density of ions at each height above the Earth and how does this density change from hour to hour, day to day, season to season, and year to year? Furthermore, we must learn something of the physical structure of the outer atmosphere, of its constituent molecules and atoms, of its temperature. Thus a knowledge of the radio technique which permits exploration of the Earth's outer atmosphere becomes essential.

IV. MULTIFREQUENCY METHOD OF DETERMINING ION-DISTRIBUTION

To obtain the distribution of ion-density with respect to height, the Breit-Tuve experiment has been extended. In that experiment a pulse of one or two ten-thousandths sec was sent upward and the height of the reflecting level was determined from the time required for the reflection to return. Suppose, for instance, that we wish to know our distance from an inaccessible cliff. If we make a loud noise, as by firing a gun, we shall hear the echo. Now sound travels one mile in five sec; so if the echo comes back five sec later we know that the sound has traveled one mile and that the cliff is therefore half this distance or one-half mile away.

In this analogy, the radio transmitter is the gun, sending impulses at regular intervals, and the sound-wave becomes the radio wave. If the wave is assumed to travel at the velocity of light, we can determine the height of reflection from the time of transit of the pulse. As a consequence, the echo-time is very short—it requires about one one-thousandth sec for the wave to travel to a height of 100 miles and return. Our analogy fails under certain conditions, however, because of the assumption that the velocity of the wave-group was that of light. Over certain portions of the path the group-velocity is less than the velocity of light, as we shall see, so that the height measured is a virtual or equivalent height which must always be greater than the actual height.

Now the number of electrically charged particles, or ions, which cause the wave to be reflected, depends upon the characteristics of the transmitted radio wave. If the pulse of radio waves is transmitted directly upward, this characteristic is simply the frequency of the wave, that is, the number of complete oscillations which the wave executes per sec. A wave of a low frequency such as 900 kc per sec—a frequency in the broadcast band—will be reflected when it encounters a density of about 10,000 electrons per cc directly above the transmitter (see Fig. 6). Then if we measure the height of the reflecting level on a frequency of 900 kc per sec, we are in reality measuring the height at which a density of about 10,000 electrons per cc exists.

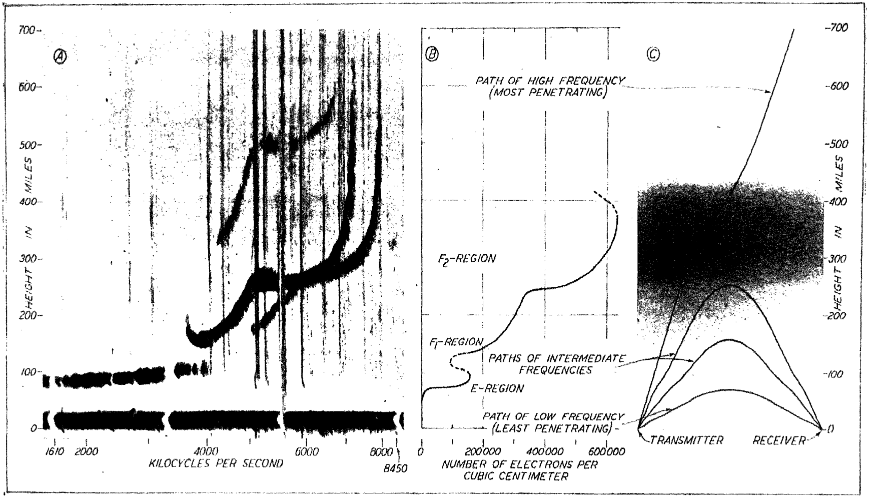


FIG. 6.—Exploration of the ionosphere: (*A*) Typical record of heights of ion-densities obtained with automatic variable-frequency equipment at Kensington, Maryland, 3 o'clock p.m., May 15, 1936; (*B*) distribution of ions deduced from (*A*); (*C*) density of ionization deduced from (*B*) showing paths of waves of various frequencies. [Diagram (*C*) shows transmitter and receiver separated for simplification, although in actual work the radio transmitter and receiver are at same station and the wave-paths are vertical.]

If we make our measurement on a higher frequency, the wave is more penetrating or we might say that the ionosphere "looked" more transparent to this wave. Therefore, a higher ion-density, that is, a larger number of electrical charges per cc, is required for reflection. For instance, a transmission upward on a frequency of 9,000 kc per sec will travel until it encounters about 1,000,000 electrons per cc before it is reflected. If such a high density of ions does not exist, the wave cannot be reflected but will continue to travel into outer space and will be lost. Then for each frequency there is a definite number of ions which will reflect the wave at normal incidence.

This, then, gives the method by which the numbers of ions at each height can be determined. In practice, a measurement of height is made first on a low frequency. The wave is reflected when it encounters the value of ion-density which corresponds to that frequency, and so the height of this ion-density is determined. Then the frequency is increased slightly and another measurement made. This gives the height of the slightly higher ion-density which corresponds to the new frequency.

As measurements are made on higher and higher frequencies, the heights of larger and larger ion-densities are determined until finally the frequency is increased to a value at which it is so penetrating that it cannot be stopped by the highest value of ion-density which exists in the region. This frequency is called the "critical frequency," for it tells us the highest density of electrical charges which occurs in the region. Now the measurements on all these frequencies, when combined, give the height of each value of ion-density and therefore the distribution of ionization through the outer atmosphere.

Let us present these arguments in more exact form [1051]. The presence of free electrons in the medium reduces its refractive index, so that in the absence of a magnetic field it becomes

$$\mu = \sqrt{1 - (e^2/\pi m)(N/f^2)} \tag{1}$$

where N is the number of charged particles of charge, e, and mass, m, and f is the frequency of transmission. This is a dispersive medium, refractive index changing with frequency. From Snell's Law, reflection occurs when the wave-direction is horizontal so that at the level of reflection

$$\mu = \sin i \tag{2}$$

where i is angle of incidence with respect to the normal. If the wave is transmitted vertically upward, reflection simply occurs when

$$\mu = 0 \tag{3}$$

so that ion-density in equivalent numbers of electrons per cc required for reflection of a vertically propagated wave becomes from (1)*

$$\left.\begin{aligned}(e^2/\pi m)(N/f^2) &= 1\\ \text{or}\qquad N &= 1.24 \times 10^4 f_{mc}^2\end{aligned}\right\} \tag{4}$$

where frequency, f_{mc}, is expressed in mc per sec and e and m are the charge and mass of an electron.

Now the height that the wave-group will travel in an increment of time is given by $dh = udt$, where u is the group-velocity. In a dispersive medium of this sort, the group-velocity is given by

$$u = \mu c \tag{5}$$

so that $dh = \mu cdt$. But $cdt = dh'$, that is, the increment of equivalent height over which the wave would have traveled had it been propagated at the velocity of light, so that

$$h' = \int dh/\mu \tag{6}$$

Now h' is the virtual height, and equation (6) states that virtual height depends upon the value of refractive index along the actual wave-path. This means, in terms of the oblique incidence picture of Figure 6, that the wave is slowed down in proportion to the amount of bending from the original angle of propagation with respect to the normal. At vertical incidence, one can imagine the propagation best by assuming that the electrical vector is oscillating perpendicular to the plane of incidence. Then as the group passes into the medium, where refractive index, μ, differs from unity, it is slowed down. When the wave reaches a level where ion-density is so great that the refractive index is zero, upward propagation of the group ceases, and the wave is reflected, returning along the same path.

If one assumes a plane Earth, such as is essentially the case over short distances, the relation between the virtual and the actual heights can be determined from the Breit-Tuve theorem [992]. This simply states that a wave leaving the Earth at a certain angle requires the same time to traverse the actual path, whatever it may be, as though it had traveled

---

* This is based on the assumption that the Lorentz polarization-correction [1057] is zero. Recently experimental evidence has been found that this is not the case, but that the Lorentz factor a should in fact be $\frac{1}{3}$. In this case the expression leading to equation (4) contains additional factors so that

$$N = 1.86 \times 10^4 f_m^2 \tag{4a}$$

Thus for $a = \frac{1}{3}$, the equivalent electron-densities are higher by a factor $\frac{3}{2}$. Ultimate decision in this matter must await discussion of the experimental evidence in the literature, but it now appears quite conclusive that equation (4a) must be used for determining equivalent electron-densities from medium or high frequencies at least.

to the apex of the projected path. The height of the apex is therefore the virtual height which is shown in Figure 7.

Ordinarily, with fairly sharp layer-definition, ion-density increases rapidly with height, so that μ differs appreciably from unity only in a small region near the level of reflection. In such cases, virtual and actual heights are not greatly different. Near a critical frequency, however, increase of ionization with respect to height is small (at the level of maximum ion-density of a region it is zero). A wave which just penetrates such a region, to be reflected by a higher region, will therefore travel at low velocity as it passes through this lower region, and at this penetration-frequency the virtual height will appear very much higher than the actual height. This retardation of the wave at penetration can be clearly seen in Figure 6 at about 3.5 mc/sec, where the wave penetrates the region, and again where it finally penetrates the ionosphere. This retardation leads to a discontinuity on the graph which serves clearly to define the penetration-frequencies. The influence of the region which has been penetrated, on retardation of the wave, disappears quickly as frequency is increased, so that at frequencies higher than the penetration-frequency the virtual height falls rapidly toward the actual height [1089, 1092].

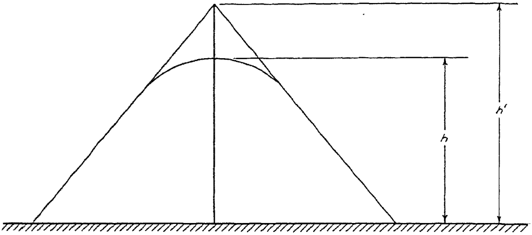


FIG. 7.—Relation of actual to virtual height as determined from the Breit-Tuve theorem.

V. DOUBLE REFRACTION IN THE IONOSPHERE

The discussion given here pretends to be neither rigorous nor complete, but rather an outline of the basic features involved in the interpretation of the observed data. There is, however, another point which must not be overlooked. It will be noticed that certain parts of the curve of Figure 6 divide into two branches; a closer examination discloses that there are really two separate sets of curves, one displaced to the right of the other. This effect appears because of the presence of the Earth's magnetic field in the ionosphere. It is, in fact, a Zeeman effect [940, 945, 952, 1173].

Now the waves reflected back from the ionosphere have different characteristics for each of these branches. Under ordinary circumstances these are quite complicated—they are elliptically polarized in opposite senses. At Huancayo, on the magnetic equator, the Earth's field is horizontal overhead and the waves travel at right-angles to the field. Under these conditions they should be plane-polarized, the electric vector of one branch oscillating along the magnetic meridian, and that of the other, across it. The former, appearing to the left in Figure 6, is termed the *o* wave-component or ordinary wave, while the latter, appearing to the right, is called the *x* wave-component or the extraordinary wave by analogy to physical optics. This matter was examined at Huancayo by Wells [1116], and waves were found to have exactly the nature which the theory predicts.

This effect not only permits confirmation of the theory of reflection but can be used as a tool to study directly the strength of the Earth's magnetic field at great heights. It may be that through this mechanism it will be possible eventually to measure small fluctuations of the Earth's field in the ionosphere with a highly developed technique. Such an experiment would be of first importance in determining the exact level at which magnetic fluctuations arise.

Because the polarizations of the two branches are different, their penetrations will be different—the *x* wave-component will be reflected from a lesser ion-density than the *o* wave-component. This difference depends upon the strength of the Earth's magnetic field. It turns out, conveniently, that the density of ionization for reflection of the *o* wave-component at normal incidence is exactly the same as though no magnetic field were present. It has been shown by Booker that the two magneto-ionic components are propagated independently in a slowly varying ionosphere, so that in all but a few very special cases independence of propagation of the *o* and *x* wave-components can be assumed. Therefore, the *o* wave-component is usually employed in computations of ion-density. The frequency at which the *x* wave-component will be reflected is related to the corresponding frequency at which the *o* wave-component will be reflected from the same ion-density by the expression,

$$(f^x)^2 - f^x f_H - (f^o)^2 = 0 \qquad (7)$$

where f^o and f^x are the frequencies of the *o* and *x* wave-components, respectively, and f_H is the natural frequency of gyration of the electron in the magnetic field, that is, $He/2\pi\,\mathrm{mc}$, where H is the strength of the field. The separation of the penetration-frequencies for the two components then becomes [1051]

$$f^x - f^o = \{[f_H \pm \sqrt{f_H^2 - 4(f^o)^2}]/2\} - f^o \qquad (8)$$

At frequencies large compared to the gyro frequency, this is very nearly

$$f^x - f^o = f_H/2 \propto H/2$$

Thus at high frequencies the observed separation of critical frequency of the two components at Washington, where H is about 0.57 gauss at the ground, is about 750 kc/sec, while at Huancayo, where H is only about 0.29 gauss, the observed separation is only about 380 kc/sec. This separation changes with height as the Earth's field falls off.

The effect of molecular or atomic ions on the propagation is inversely proportional to their masses, so that, unless the number of such ions is preponderantly great, their presence is unnoticed. Assuming the heavier ions to have a mean mass of about 5×10^4 times the mass of an electron, it takes about 1,000 times as many molecular ions as electrons to make their presence evident [976]. With this number present, the separation of penetration-frequencies of the two magneto-ionic components is reduced by about two per cent, the reduction becoming rapidly more pronounced as the number of such ions increases. From information obtained in this way it has been determined that above about 100 km the number of heavy ions cannot exceed the number of electrons by more than 1,000 times as a limit. There is reason to believe that in the F_1- and F_2-regions the ratio of of molecular and atomic ions is much smaller than this limit. By an independent experiment involving the behavior of the extraordinary ray below the gyro frequency, one finds that in the lower E-region there must be just about 1,000 times as many such ions as electrons.

VI. AUTOMATIC MULTIFREQUENCY METHODS AND THE RECORDS PRODUCED

From the observational point of view it is necessary to record the height of reflection at each of all frequencies on which reflections can be observed—the complete curves to be obtained at intervals short enough so that intervening changes are not great. In early equipment these measurements at successively greater frequencies were conducted by an operator who made each adjustment of frequency manually and who then measured the height of each ion-density visually on an oscilloscope [1051, 1089, 1092]. Such methods were slow and cumbersome. An experienced observer required from one to two hours to make a complete determination of the distribution of ionization through the whole of the ionosphere. During this interval the ionosphere might have changed very materially. The first improvement was to record the results photographically. Even then continuity of measurement by such a method is impossible without an unreasonably large personnel.

To meet this situation more effectively, the completely automatic equipment shown in Figure 8 was developed by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington [982]. In its design, the suggestions of Gilliland [1016] were incorporated to synchronize the transmitter and the receiver. Successive observations of virtual height are made automatically at exceedingly small increments of frequency over the range from 0.516 to 16.0 mc/sec. Each sweep through this frequency-range is completed in 15 minutes, four sweeps being made each hour. In this manner the virtual height of each ion-density in the range 3.1×10^3 to 3.1×10^6 equivalent electrons per cc is measured, and from the curves thus formed on the photographic trace, the critical frequency, minimum virtual height, and other characteristics of each region are determined. Typical records are shown in Figures 6-*A* and 9.

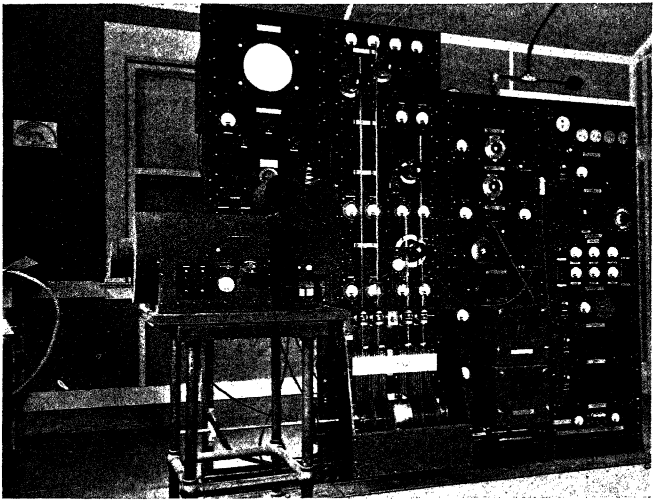


FIG. 8.—Automatic multifrequency equipment for measurements in ionosphere.

The base-line consists of thousands of pulses of about 100 microseconds duration on frequencies beginning at 16.0 mc/sec and spaced at small increments of frequency down to 0.516 mc/sec. The reflections from each transmitted pulse are recorded along the vertical scale which is appropriately calibrated in virtual height as determined from the time for the pulse of waves to travel to the reflecting stratum and return. Because successive reflections from a given region form a coherent trace on the record, the resultant curves appear continuous as contrasted with the incoherent spots of interference and noise which are scattered on the trace in a random manner and therefore appear only as fogging on the record.

The development of the automatic equipment has been completed only recently, so that one can as yet draw upon the more complete data so obtained only to a limited extent. During 1937, operation of one unit was commenced at the Huancayo Magnetic Observatory, and the installation of a similar unit at the Watheroo Magnetic Observatory was completed in 1938. In the meantime we must turn to observations by the earlier manual and fixed-frequency methods to obtain a picture of the ionosphere itself. The longest continuous set of observations is that of the National Bureau of Standards at Washington (39° north, 75° west), extending back to 1931 [1018, 1019, 1051, 1054]. Long sets of data are also available from the magnetic observatories of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington [976, 977, 981] at Huancayo, Peru (12° south, 75° west) and at Watheroo, Western Australia (30° south, 116° east). Data are also available from many other locations, but these three sources will be used principally because of their availability and completeness.

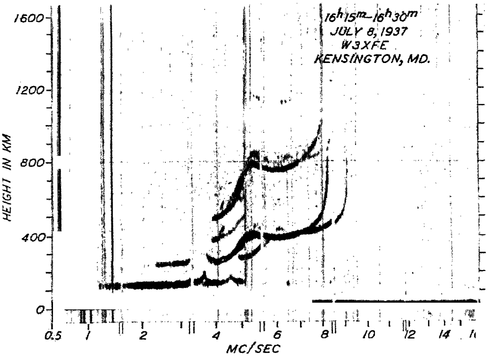


FIG. 9.—Typical record of ionosphere obtained with automatic multifrequency equipment.

VII. THE GENERAL NATURE OF THE IONOSPHERE

We find that the ionosphere is not a simple region of ionization, as was first thought. The original experiments of Breit and Tuve indicated a complicated structure, and early experiments of Appleton showed that two regions must exist. Now we know that it consists of two and, under some conditions, three principal regions of ionization. The lower of these regions, technically known as the *E*-region, is around 100 km (about 60 miles) above the Earth's surface, while the upper regions, technically known as the F_1- and F_2-regions, are around 210 km (about 130 miles) and 300 km (about 185 miles) overhead, respectively. These are average daytime values, as the heights vary a good deal under different conditions.

Imagine traveling upward on a typical summer noon at Huancayo in some conveyance which could take us to the outer reaches of the atmosphere. Near the Earth we find a few thousand ions per cc, due to cosmic rays and other sources. From about 25 km (15 miles) to about 65 km (40 miles) we travel in a region in which little is now known concerning the ionization from actual experiment, though it must be relatively low.

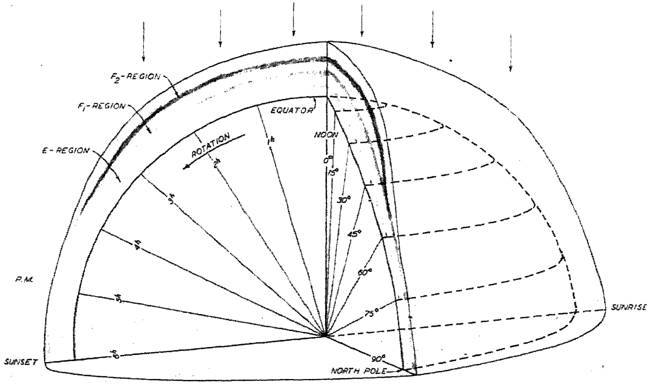


Fig. 10.—Ion-distribution in sunlit hemisphere in the ionosphere.

At a height of about 65 km we observe that the density of ionization increases, gradually at first and then with increasing rapidity. At about 100 km (60 miles) the increase becomes so sudden that the density of ionization changes by a factor of 10 or more within a few km. A little above this we reach the maximum density corresponding to about 180,000 electrons per cc. This is the *E*-region of the ionosphere.

The change just below this height is abrupt, and therefore the term "layer" is sometimes applied. Just above this there is evidence for believing that the ion-density decreases slightly. Then it increases again—very rapidly at a height of about 190 km. The maximum is reached somewhat above 220 km (say 130 miles), where we find that the ion-density corresponds to about 330,000 electrons per cc. This is the F_1-region. As we continue upward the ionization remains nearly constant, though it may decrease or increase a little, until at about 300 km (say 185 miles) a third sharp increase occurs. The density of ionization near this level may reach as much as 1,000,000 electrons per cc.

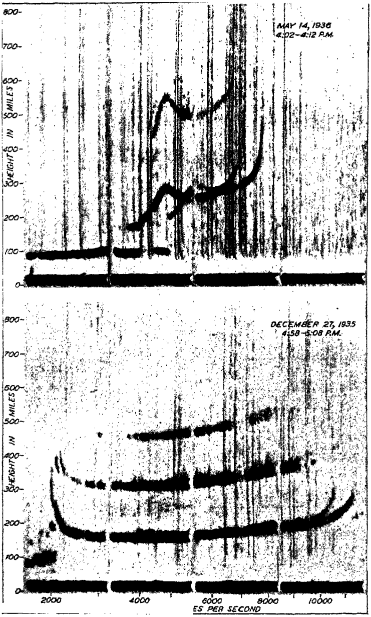


FIG. 11.—May and December conditions in the ionosphere (structure changes radically with time of year), Kensington, Maryland (Station W3XFE).

It must be remembered that this distribution is for a particular time of day, season, and year and that under other conditions the situation might differ materially. Nevertheless, the first two regions, one at about 100 km and the other above 220 km, will be found over any part of the Earth as far as we now know, though the maximum densities might differ tenfold.

We have spoken of two regions being present always—the third has a more transient existence. This third, or F_2-region, exists separately only under the more direct rays of the Sun [977]. It appears to bulge outward from the next lower or F_1-region, which is depressed downward below it. This bulge or "blister" seems to center directly under the Sun, so that at this point the F_2-region is in general highest and most widely separated from the F_1-region below. If we move away in any direction, the height of the upper region falls until it finally merges with the region below. The separation between the two regions is scarcely perceptible in a position where the Sun's altitude is less than about 45°. Therefore, the F_1- and F_2-regions appear separated only in a circular area under the Sun and consequently are in the center of the sunlit hemisphere. This bulge covers an area of about three-tenths the sunlit hemisphere. Where the two regions merge at the outside edges of this bulge, the resultant region is known simply as the F-region. Because their ionizations add together, this new region has many of the characteristics of the more highly ionized F_2-region.

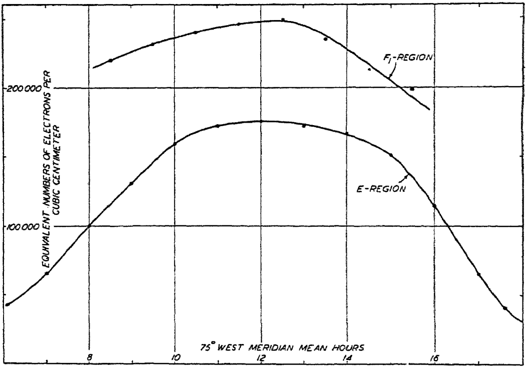


FIG. 12.—Typical example variation of maximum ion-density in E- and F_1-regions during the day, Huancayo Magnetic Observatory, May, 1934.

Because the Earth's axis is tilted about 67° with respect to the plane of its orbit, the center of this area rotates around the Earth with the Sun along the Tropic of Cancer in the northern summer, gradually shifting to the Tropic of Capricorn as the seasons reverse. At Washington, for example, the separation of these upper regions is quite distinct during the midday hours in the summer when the Sun reaches an altitude of about 78° above the horizon, but in midwinter these regions are entirely merged because the Sun reaches an altitude of only 28° at midday, when Washington is well outside the 45° zone. As a consequence, the nature of the records changes radically, as shown in Figure 11.

We see, then, that instead of the simple region which was originally conceived, the ionosphere is complicated, involving two main regions with a tremendous bulge above the upper of these to form still a third region of ionization. Why should three regions exist? What is their origin?

VIII. THE E- AND F_1-REGIONS

We can learn something of this from the characteristics of these regions. We shall consider the two regions, E and F_1, together because in some respects they are similar in detail.* At night the ionization of the E-region is low. The F_1-region can be distinguished separately only after the Sun has risen. After sunrise the ionization increases rapidly, reaching a maximum toward noon and decreasing thereafter toward evening. Then in general during the day the number of ions in these regions is proportional to the amount of sunlight upon them.

Let us observe the change of these regions with season. The number of ions is lower in the winter than in the summer. This is true in both hemispheres, so that when the highest numbers of ions are observed at noon in one hemisphere—as during June at Washington—lower numbers are observed in the opposite hemisphere—as at the same time at Watheroo. This inverse relationship between Northern and Southern hemispheres can be seen in Figure 13. From this we see that at all times of the year the ion-density of these two lower regions during the day is in general proportional to the sunlight incident upon them.

A final and critical test is obtained by observations during an eclipse of the Sun. In 1932 such an eclipse occurred in North America, being about 90 per cent total at Washington [1050]. It is fortunate that for these observations the eclipse need not be total, nor does obscuration of the Sun by clouds interfere with the measurements in the least. This eclipse permitted a direct determination of the force active in ionizing these regions. It was found that, as the Sun's disk was obscured, the ionization immediately decreased, again increasing as the Sun came into view. Because only sunlight can have such an immediate effect, we may conclude that it must be the principal source of the ionization of the E- and F_1-regions during the daytime.

---

* In discussion of the E-region, one finds frequent reference in the literature to a D-region [1071] which lies below the E-region. Present evidence indicates that from the standpoint of ion-distribution this D-region may be the downward extension of the E-region from about 90 to 60 km. There is evidence, however, that ion-production in this region involves a different light-absorption from that for the E-region near its maximum. Furthermore, because the collisional frequency between ions and neutral molecules is high owing to greater atmospheric density, intense ionization of this region produces great absorption of the waves traversing it. For these reasons we should perhaps distinguish this lower portion of the E-region, between about 60 and 90 km, explicitly as a separate or D-region. This distinction has not been made here, however, because it might imply a separate ion-bank which evidence does not now indicate to be the case. Limitations of the multifrequency method at very low frequencies prevent extension of these methods to examination of this lower part of the E-region except through the implications of the low-frequency absorption-limit which is discussed in Section X.

At night, because the F_1-region has merged with the F_2, its identity is completely lost in the single F-region which has been thus formed. In the case of the E-region, one might suppose that ion-density would decay exponentially through the night in a manner determined by the pressure, temperature, and density of ionization. In general, from observations at the Kensington Experimental Station near Washington, such does not seem to be the case. In late afternoon, the maximum ion-density of the E-region decreases until some time after sunset, when an irregular replenishing process of some sort becomes apparent. Usually in early evening the equivalent electron-density reaches about 10^4 per cc, dropping to this value along a relatively smooth curve. At the same time, the height increases in the order of ten km. Following this decrease, irregular increases in ion-density are observed over periods of 15 to 90 minutes, each followed by a slow decay in density. With each increase, a drop in height of a few km is observed, followed by a slow rise as decay again becomes apparent.

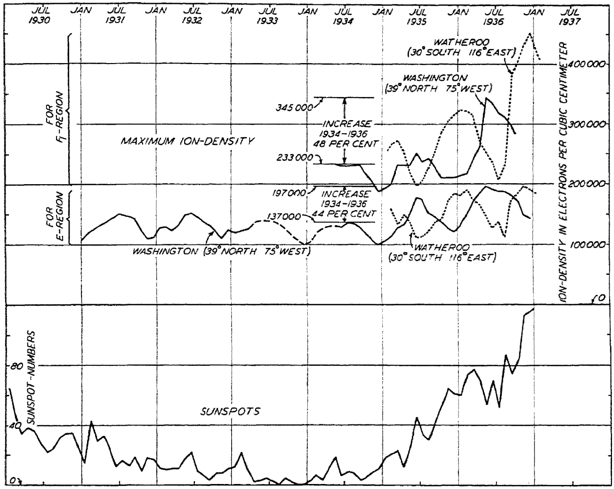


FIG. 13.—Monthly averages of maximum ion-density for E- and F_1-regions of the ionosphere and of sunspots.

Thus in temperate latitudes at least, the ion-density of the E-region at night seems to be maintained by an irregular process so that the penetration-frequency fluctuates between about 700 and 1,600 kc/sec throughout the majority of nights. The cause of this replenishing process is not definitely known. It may be a minor aspect of the phenomenon known as "sporadic E-region ionization" which will be discussed in section XI. It should be possible to settle this point with information obtained as a function of latitude with the multifrequency technique—a test just now becoming possible.

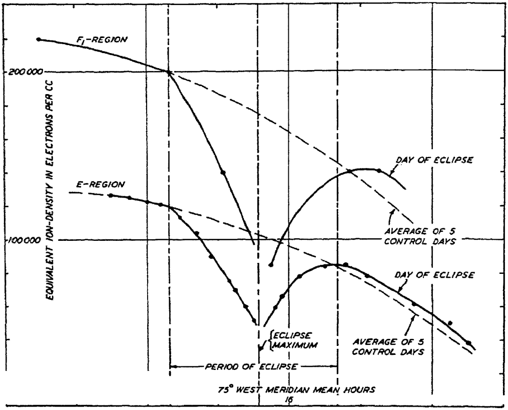


FIG. 14.—Solar-eclipse effect in E- and F_1-regions on August 31, 1932, Kensington, Maryland; as the Sun's disk was obscured, ionization immediately decreased, again increasing as the Sun came into view (*after Kirby, Berkner, Gilliland, and Norton*).

Change of maximum ion-density in E- and F_1-regions with changing sunspot-number is particularly intriguing. As demonstrated in Figure 13, there has been a steady change in monthly means of ion-density for both regions, as solar activity, measured by averages of sunspot-numbers, has changed. Up to June of 1937, the mean summer-noon ion-density of the E- and F_1-regions had increased by 44 and 48 per cent, respectively, over corresponding values observed during the minimum of solar activity in 1933–34.

Attempts to correlate daily values of sunspot-number and ionization of E- and F_1-regions have so far met with failure. Maximum values of ion-density of these regions are repeated with remarkable regularity from day to day, with only seasonal and longer-time trends. Variations of more than about two per cent for the E- , and about five per cent for the F_1-region at corresponding times of day from one day to another are uncommon unless accompanied by magnetic disturbances. At the same time daily values of sunspot-number may fluctuate enormously. This indicates that the ultraviolet light which is responsible for the ionization of these regions is changing much more steadily and smoothly than is indicated by the violently fluctuating sunspot-number. It appears that we are measuring a much more fundamental change in the Sun—one heretofore unknown—than is indicated by variations of sunspots. As has been remarked elsewhere, it is probable that sunspots are merely an external, visible manifestation of some more fundamental variation of the Sun—a variation which we can see more clearly from our new point of vantage at the top of the atmosphere.

IX. THE F_2-REGION

We have yet to deal with the F_2-region, this outer "bulge" which appears only when the Sun is high overhead. This region does not behave in the same manner as the lower regions. It is found that violent fluctuations in ionization are common within a space of a few hours, while there may be radical differences from one day to another. The trend of change in ion-density during the day is quite different in June and in December, and there are marked dissimilarities in this trend at each of the observing stations, which are widely separated over the Earth. This region might be called the "anomalous" region.

The complexity of change in the F_2-region makes it in many ways the most interesting for study. Because of greater irregularity, it becomes less easy to generalize with the limited data at hand. It appears certain that its principal ionizing agent emanates from the Sun for a diurnal variation of height and ion-density having a period of the solar day and is always present.

Consider first variations of virtual height of the F_2-region [982]. The most important fluctuation in average height is a function of the Sun's altitude. In the temperate zones (at Washington and Watheroo) the height is greater on the average when the Sun is high. This, of course, follows directly from the precept of bulge-formation of the F_2-region. At Huancayo, in the equatorial zone, the daytime height is usually as great as or greater, on the average, than heights in the middle temperate zones. Although there it rises and falls with solar altitude during the day as in the temperate zones, there is a seasonal tendency for the height to vary inversely with the noon altitude of the Sun. In other words, the maximum diurnal variation in height tends to occur about the time the Sun passes its farthest north, or south, declination. This is illustrated in Figure 15. Thus, while the changes in height appear to be on an average principally seasonal in character, there is indication that the nature of this seasonal change is reversed in equatorial regions.

A second important effect is the "bite-out" effect [982]. At Huancayo, where the F_2-region exists always during midday hours, there is a bite-out in the diurnal curve of maximum ion-density as shown in Figure 16. A peak of ion-density is reached in morning and again in late afternoon, with a valley near noon. At Washington during midsummer, when the F_1- and F_2-regions are separated, a somewhat similar effect is noticed, though the morning maximum is usually very flat, or absent. The afternoon maximum occurs near sunset. During winter months, when F_1- and F_2-regions are merged at Washington, the curve of the resultant F-region becomes more simple, reaching its maximum in much the same

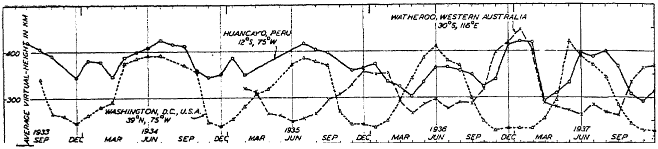


FIG. 15.—Comparison monthly average noon values F_2-region minimum virtual heights.

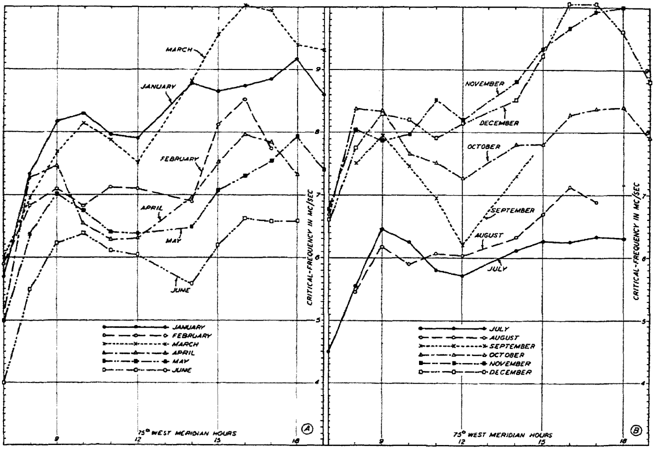


FIG. 16.—F_2 critical-frequency, monthly averages diurnal variation, Huancayo Magnetic Observatory: February to June, 1934, and January, 1935 (A); July to December, 1934 (B).

way as the lower regions, though perhaps an hour or two after noon. In contrast to Washington, practically no bite-out is observed at any season at Watheroo, though one is sometimes slightly apparent during local winter (May, June, July, and August)—the same months it appears at Washington. This can be seen in Figure 17. When observations from Washington and Huancayo became available, it seemed that the effect could be explained by a process of heating and expansion in the F_2-region when the Sun was most nearly overhead. The Watheroo data, however, do not seem to be explained by such a process, for the bite-out effect seems to be entirely absent at Watheroo when the Sun's altitude is highest.

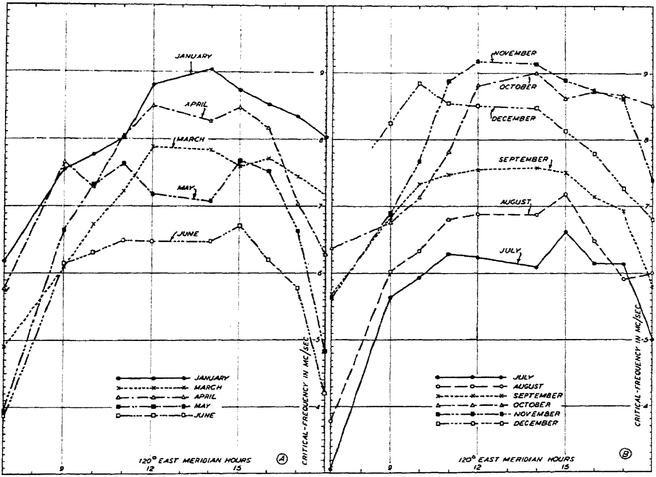


FIG. 17.—F_2 critical-frequency, monthly averages diurnal variation, Watheroo Magnetic Observatory: March to June, 1935, and January, 1936 (A); July to December, 1935 (B).

Non-seasonal changes provide the third effect to be considered [980, 982]. We imagine a seasonal effect to be one which is the same function of changes of local zenith-angle with season in both hemispheres. Maximum values of F_2-region ion-density measured at noon do not change in the same way with season at Washington, for example, in the Northern Hemisphere and at Watheroo in the Southern Hemisphere. This is demonstrated by Figure 18 where average values of maximum noon critical frequency squared (which is proportional to ion-density) are plotted for these stations over the interval 1935–37. Variation of maximum ion-density at Washington has a single important maximum in northern winter and a single important minimum in northern summer. On the other hand, variation at Watheroo has two maxima of comparable importance at the equinoxes, and two minima of comparable importance, one in winter and one in summer. It would be manifestly untrue to say that the seasonal variation at Watheroo referred to southern midwinter as origin of time is even approximately the same as the seasonal variation at Washington referred to northern midwinter as origin of time. This destroys the basis for assuming that the variation of either station simply represents what is customarily regarded as a seasonal effect.

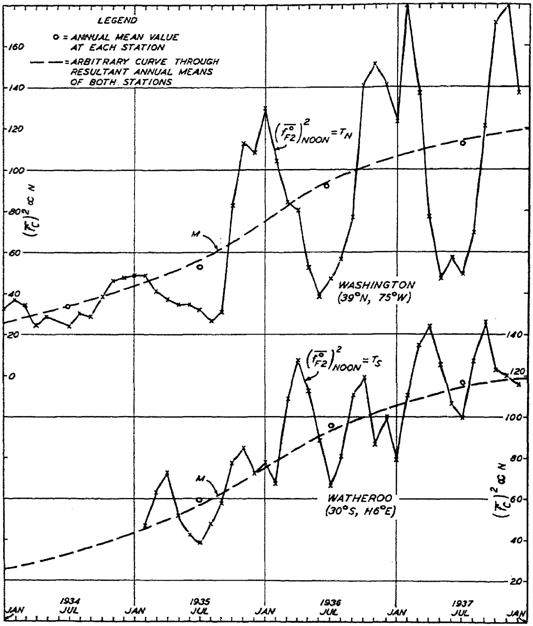


FIG. 18.—Monthly mean values of F_2 critical frequency squared as measured at noon.

This apparent discrepancy can be resolved if variations at the two stations are divided into two components as in Figure 19. One of these, denoted by *S*, is in the same phase at both stations, while the other, denoted by A, is in opposite phase in the two hemispheres. Two curves are shown for S, the upper curve to which is referred the ion-density at Washington, and the lower (inverted) to which is referred the ion-density at Watheroo. The positive direction is always measured from S to A so that the area above A represents the ion-density at Washington, while the area below A represents the ion-density at Watheroo. In essence, the variation which is out of phase at the two stations, A, is referred to the variable base-line, S, which is the component in phase at both stations. The principal part of this in-phase variation has had a period very close to one year. It is not a seasonal variation in the ordinary sense. Its amplitude is about equal to that of the seasonal variation. It is because of this component, which is common to both stations at the same time, that the changes of ion-density shown in Figure 18 were so radically different for the two stations. When the non-seasonal component is removed, the seasonal changes in the two hemispheres become mutually consistent. Examination of variation in noon values of F_2 critical frequencies for such other stations as are available shows a similar non-seasonal component in the same phase, though it is impossible to generalize from data from so few stations.

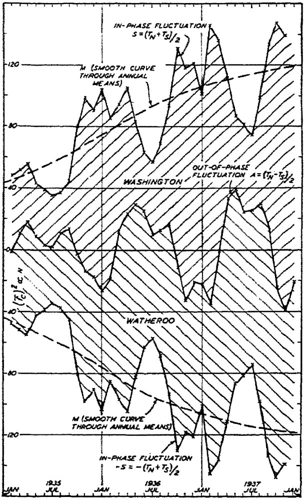


FIG. 19.—Ion-density plotted with respect to out-of-phase fluctuation $+A$ (ordinate differences yield curves of Figure 18).

When the non-seasonal change is removed, the remaining seasonal change which is given principally by A is found to have smallest values of ion-density in local midsummer and larger values of ion-density in local midwinter. This is opposite to the change which has been observed for the lower E- and F_1-regions and requires a special explanation. To account for this inversion of seasonal variation in the F_2-region, as well as the seasonal change of virtual height, hypotheses of heating and expansion were proposed by Hulburt [1043, 1044], by Appleton and Naismith [958], by Harang [1030], and others. They suggested that ion-density decreased in local summer because of an expansion of the outer atmosphere under the more direct rays of the Sun, so that, although the total number of ions might be greater through the whole region, the density in any unit-volume would be diminished. As we have already seen, this hypothesis does not explain the observation of the bite-out effect at Watheroo. No reasonable explanation has yet been offered to account for the non-seasonal effect. Because the underlying causes behind the effects described are not well understood and must remain controversial until enough data have accumulated clearly to define their singularities and relationships, we must conclude that as yet the theory of the F_2-region is by no means complete.

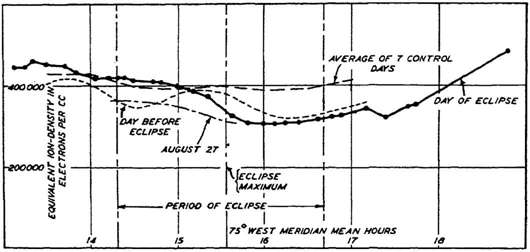


FIG. 20.—Solar-eclipse effect in the F_2-region on August 31, 1932, Kensington, Maryland (*after Kirby, Berkner, Gilliland, and Norton*).

This is emphasized by the nature of results during an eclipse. Observations of the eclipse of August 31, 1932, made near Washington [1050] are shown in Figure 20. Instead of a large decrease of ion-density as was observed in the lower regions (see Fig. 14) at the time of the eclipse, no really significant departure from the control-data was observed. In fact, ion-density during the eclipse remained about the same as on two of the control-days. Another observation during an eclipse by Kirby, Gilliland, and Judson [1052] on February 3, 1935, at Washington did not agree with this earlier result for there was a significant decrease during the eclipse. During the eclipse of June 19, 1936, the observations of Minohara and Ito [1483] agreed with the results in 1932. The tendency seems to be that, when observations during an eclipse are made where the F_1- and F_2-regions are widely separated, no significant change in ion-density of the F_2-region is observed, this situation occurring only in summer in low or middle latitudes. When the regions are merged, as in winter at middle or high latitudes, a definite decrease in ion-density occurs during the eclipse. This change is probably greater than can be accounted for because of eclipse of the ionizing agent in the F_1-region alone.

It is thus impossible as yet to say much about the ionizing force responsible for the F_2-region. Some of the effects, such as those described during the eclipse and at the time of magnetic disturbances, as will be indicated later, seem to indicate ionization by the bombardment of particles. Other effects seem more readily explained by ultraviolet-light ionization. It may well be that both processes are involved. In summing up the situation, one must face the fact that the data at present are too meager to permit the broad generalizations necessary to formulation of a complete, consistent theory for the F_2-region. The effects which have been described must be delineated more clearly by wide-spread and consistent observation.

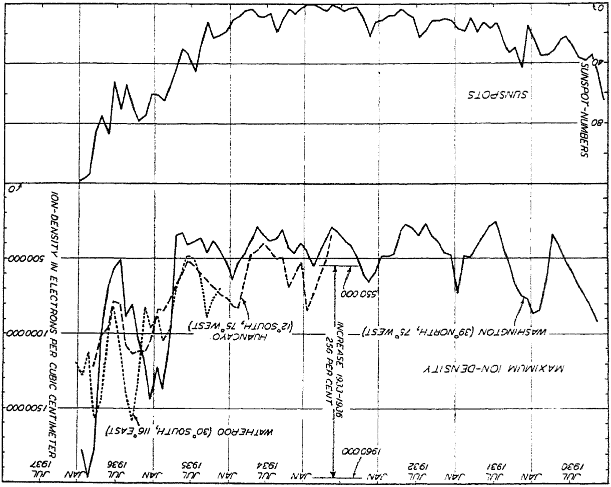


FIG. 21.—Monthly averages of maximum ion-density for F_2-region of the ionosphere and of sunspots.

It is apparent from Figures 18 and 19 that the ion-density of the F_2-region is changing radically from year to year [1045]. The dashed lines connect the annual averages for both stations for successive years. The change over the years 1930–36 is shown in Figure 21, where monthly means of noon ion-density for Washington, Watheroo, and Huancayo are compared with monthly means of sunspot-number. The range of variation is seen to be about proportional to sunspot-number—in fact annual means of ion-density have changed almost linearly with annual sunspot-numbers over the interval. This indicates that the change in ion-density is closely related to solar activity. Range of ion-density for the F_2-region has increased more than four times since the last sunspot-minimum, an increase which is enormous compared with that of 40 or 50 per cent for the lower regions. Thus it may be that the F_2-region will become the best quantitative indicator of solar activity which has yet been found since, so far as is known, no other terrestrial phenomena change so sensitively with solar activity. Curiously enough, fluctuations of ion-density from day to day appear to be uncorrelated with changes in sunspots. As a consequence, one is again led to the view that sunspot-activity may be but a visual manifestation of a more fundamental underlying solar change which is also related to changing ion-density.

X. RADIO FADE-OUTS ACCOMPANYING BRIGHT CHROMOSPHERIC ERUPTIONS

We proceed now to consideration of irregular effects of limited time-duration which have been disclosed through investigation of the ionosphere. These effects are of considerable importance in interpretation of phenomena such, for instance, as the short-time changes in the Earth's magnetism in terms of the ionization of the Earth's outer atmosphere. Earlier in this chapter the radio fade-out was introduced as a specific example of solar and terrestrial relationships of far-reaching influence. The importance of this effect is such as to warrant more thorough consideration in terms of the layer-structure which has been outlined.

As early as 1859, Carrington and Young observed that accompanying a tremendous solar outburst of September 1, 1859, the magnetic elements were simultaneously disturbed. This was considered in some detail by Balfour Stewart and others. Although this observation led to widespread speculation concerning possible solar and terrestrial relationships, it was practically discarded as coincidence following further search for similar events—a search marked largely by the paucity of reliable observational data. In 1903, Birkeland, in examining the nature of 19 magnetic bays, found one of distinctly different character from the others (of a type now known to be associated with bright chromospheric eruptions). Yet its real significance remained unrecognized in the absence of the necessary related information. It is concerning such earlier observations that Bartels [973] is led to remark that "if radio fade-outs had not given such strong evidence of ionospheric disturbances simultaneous with solar eruptions, it is not impossible that the comparatively small, though distinct, terrestrial magnetic effects would still have escaped detection." This is material evidence that through correlated effort in many fields come major contributions to our comprehension of solar and terrestrial relations.

Late in 1935 Dellinger [1004] made his first announcement of a peculiar series of radio fade-outs coincident at a number of stations in the daylight hemisphere. These had occurred during the previous year or two and appeared to coincide with bright chromospheric eruptions. They were often accompanied by a distinct magnetic change. Independently, Jouaust, in correspondence with other investigators, described a similar fade-out effect which he had observed in Europe. These observations were followed immediately by a series of reports of the effect in some or all of its phases which led rapidly to confirmation of the fact that with certain bright chromospheric eruptions there occurred a radio fade-out in the sunlit hemisphere, often accompanied by the magnetic and earth-current effects illustrated in Figure 1 [1087, 1109]. Probably the most important immediate inference was from the analysis of the magnetic effect by McNish which was based upon observations at a number of locations [1059]. He showed the magnetic change which took place to be always an augmentation of the magnetic diurnal variation. Chapman [1000] has recently pointed out that the isolated magnetic disturbance, analyzed by Birkeland as markedly different from the usual type, was one which must have accompanied a chromospheric eruption.

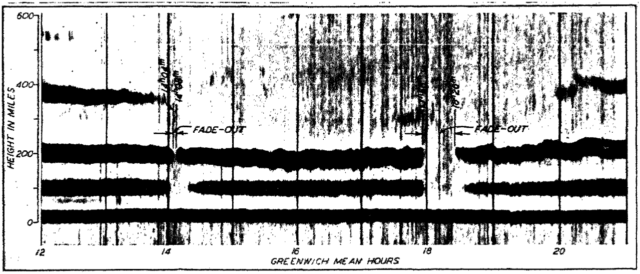


FIG. 22.—Examples of radio fade-outs, Huancayo Magnetic Observatory, May 28, 1936.

Examples of radio fade-outs observed at the Huancayo Magnetic Observatory are shown in Figure 22 [979]. This record was obtained by measuring the height of reflection continuously on a fixed frequency of 4.8 mc/sec. At 14^h04^m the echoes disappeared for four minutes, and again at 17^h58^m the reflections were gone for 28 minutes. At these times, similar effects occurred everywhere in the central portion of the sunlit hemisphere, decreasing in intensity toward the twilight zones, and disappearing entirely in the night hemisphere. In every case where the effect can be definitely confirmed as such, it is accompanied simultaneously by a bright chromospheric eruption.

One may summarize the information obtained from such records as follows: Fade-outs appear only in the sunlit hemisphere and are most intense within about 30° of the sub-solar point. The correlation between monthly numbers of fade-outs and sunspots is $+0.53 \pm 0.10$ for the data from Huancayo. The evidence supports Dellinger's hypothesis of the origin of these effects in the bright chromospheric eruptions. There is a strong tendency for fade-outs to be grouped—when one appears it is often followed by a series of fade-outs, which occur around the Earth in the sunlit hemisphere. The beginning of a fade-out is essentially coincident at all stations. The duration of fade-out is short—more than 60 per cent of fade-outs last less than 15 minutes. There is some doubt concerning a recurrence-tendency. In the earlier observations of Dellinger, fade-outs were observed at intervals of about 54 days, which he interpreted as indicating a recurrence-tendency of this period. The data from Huancayo fail to show this recurrence, and it seems doubtful whether such a recurrence-tendency actually exists.

Though Figure 22 shows the nature of the fade-out on one frequency, one must know the effect on waves of every radio frequency, which would ordinarily be reflected, if its exact nature is to be determined. This is best done by observation, the automatic multifrequency technique already described being used. Figure 23 shows the result of such an observation for the fade-out of July 31, 1937 [979]. This fade-out coincided with a bright chromospheric eruption of intensity 3 observed at both the Mt. Wilson Observatory and the Huancayo Magnetic Observatory. The following description of the eruption has been furnished by Dr. Richardson of the Mt. Wilson Observatory:

> An eruption of intensity 3 was first photographed by us at $11^h\ 12^m$ (75° west meridian time) over a large spot-group at 23° north, 67° east. We have no earlier observations of this region, so the time of commencement is unknown; but as the flocculi were increasing in brightness when first seen, it might be estimated that the outburst began about 11^h. Maximum brightness was at about $12^h\ 04^m$ with the end occurring in the neighborhood of $12^h\ 30^m$. The eruptive flocculi covered an unusually large area.

The maximum brightness of the eruption coincided very nearly with the central time of the fade-out.

The dashed lines of Figure 23 show the hourly mean value comprised of four observations made during the hour on each of six days involved in the mean. Individual points show observations for each 15-minute interval on the day of the fade-out. The fade-out is outlined by the extension of the lower absorption-limit from its normal low-frequency value through the frequency-spectrum under consideration. Thus reflections are obliterated on all frequencies during its most intense part. It is at once evident that the duration of the fade-out at normal incidence is dependent upon observing frequency and, as a consequence, it will also depend somewhat upon the output-power of the transmitter and upon the sensitivity of the receiver.

Examination of the curves for F_1-region and F_2-region critical frequencies shows that at the onset of the effect there is no significant change

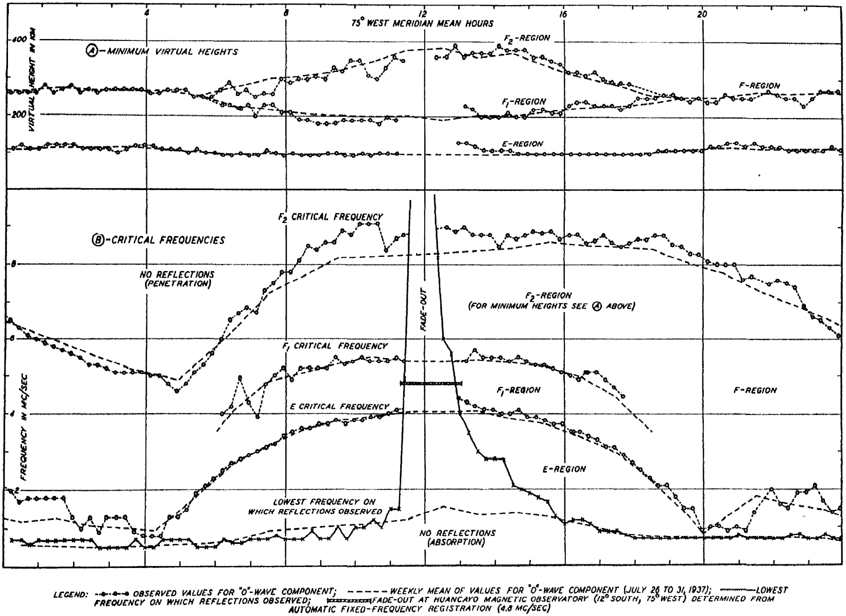


FIG. 23.—The ionosphere showing radio fade-out July 31, 1937, determined from automatic multifrequency registrations, Kensington, Maryland (39° 01′ north, 77° 05′ west).

in critical frequency and that, when reflections reappear, critical frequencies have not deviated from the normal trend in the least—in fact the fluctuations are rather smaller than often observed around the same hours on preceding and following days. There does, however, appear to be a small but significant increase in the *E*-region critical frequency immediately after the fade-out. Assuming this to be a result of the effect of fade-out, equilibrium-conditions in the *E*-region are not immediately reestablished at the end of the fade-out. Equilibrium-conditions would be reached still more slowly in the upper regions because of decreasing atmospheric density with height. One can reasonably suppose, therefore, that had any increase in ion-density occurred in the upper regions, either it would become apparent at the onset of the effect or a small residual increase in critical frequency of these regions would persist through the termination of the fade-out on high frequencies. The absence of any such increase coupled with the fact that unchanged values of F_1-region and F_2-region critical frequencies are observed long before the end of the effect on the lower frequencies leads to the conclusion that no appreciable change has occurred in the maximum ion-densities of the F_1- and F_2-regions during the fade-out.

Similarly at the end of the fade-out there has been no significant change in the virtual height of the F_1- or F_2-region which cannot be explained by effect of lower regions on the retardation of the wave. The height of the *E*-region, however, has undergone a change which seems significant. The change in the *E*-region near the level of maximum ion-density cannot alone explain the phenomenon of echo-disappearance. The data of Figure 23 show that the fade-out effect is perceptible in the lower frequencies more than two hours after the *E*-region appears quite normal. Thus the effect predominates below *E*-region levels. It appears to extend upward only far enough into the *E*-region to leave it disturbed at the end of the fade-out.

The evidence presented above has demonstrated that the fade-out effect must be an absorption of the radio wave in the region below about 100 km. The mechanism appears to be an increase in ion-density in this region of high collisional frequency, leading to the dissipation of radio waves which usually penetrate the region below about 100 km without appreciable loss. Best, Ratcliffe, and Wilkes [985] have shown that ionization of the region from about 60 to 100 km is responsible for the reflection of very low radio frequencies. Taking into account the mechanism involved in the reflection of long waves, one immediately expects that low radio-frequency signals should increase in intensity during radio fade-outs, if the transmission-path passes near the sub-solar point. Bureau [993], observing intensity of atmospherics on low radio frequencies, has noted just such an increase which may be attributed to improved transmission-conditions during the radio fade-out as a consequence of increased ionization in this region above about 60 and below 100 km.

With this information we can isolate the region in which the disturbance principally occurs, namely, between about 60 and 100 km. With the advent of a bright chromospheric eruption, the ultraviolet light from the eruption is absorbed selectively at this level. With this absorption an intense ionization is produced which, because of the high collisional frequency in the region, absorbs the radio waves that ordinarily pass through the region. Now this level is about the height at which electric currents must flow in the atmosphere to produce diurnal variation of terrestrial magnetism in accordance with the atmospheric dynamo-theory of Stewart and Schuster. In his analysis of the magnetic effects which accompany fade-outs, McNish concludes that the magnetic changes come about because of increased current-flow contingent upon the increased conductivity of this region, the height of which has been determined by radio methods. Because the magnetic effects always appear as an augmentation of the diurnal variation, even where anomalous diurnal effects are observed and because the heights have been established by radio methods, he believes the evidence sufficient to establish the general validity of the Stewart-Schuster theory of magnetic diurnal variation in this region.

The data of Figure 23 give strong evidence for formation of the different regions by processes of selective absorption. It is seen that the intense ionization occurred in the lower *E*-region (or *D*-region) without any appreciable change in the F_1- or F_2-region. Because the ionizing radiation which affects the lower ionosphere during the fade-out must have traversed the upper regions, the absorption of this radiation in the upper regions must have been negligible. This indicates that the absorption is a selective one, involving the absorption-band of a particular molecular or atomic species, and that the absorption-coefficient is small, permitting the radiation to penetrate a few cm of atmosphere before being absorbed. The production of ionospheric regions by processes of selective absorption is only now being investigated, the chief limitation being lack of knowledge of nitrogen absorptions in the far ultraviolet.

XI. SPORADIC INTENSE *E*-REGION IONIZATION

A second irregular effect which we must consider is sporadic ionization of the *E*-region [957, 959, 978, 1051, 1084, 1086, 1090]. Normally ion-density of the *E*-region undergoes relatively smooth diurnal and seasonal variations as we have already seen. It was demonstrated that this was produced by ultraviolet radiation from the Sun.

Occasionally, reflections of great magnitude are observed from the *E*-region when frequencies much higher than the normal critical penetration-frequency for the E-region are used [957, 959, 1084, 1086, 1090]. Reflections from the upper regions, otherwise apparent on these frequencies, may be entirely obscured. It is therefore supposed that an abnormal or "sporadic" ionization must have occurred in the E-region. Such events may occur at any hour and last for a few minutes or even several hours. Ion-density during such periods often exceeds 10^6 equivalent electrons per cc, as deduced from the penetration-frequency.

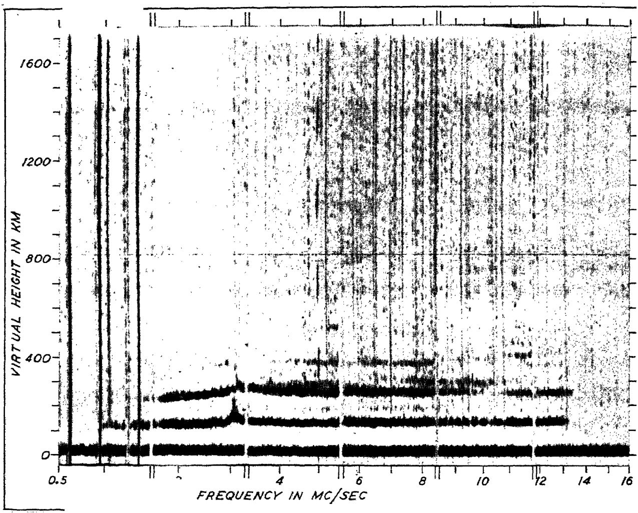


FIG. 24.—Sporadic intense ionization of E-region, Kensington Experimental Station, July 14, 1937, 17^h 30^m to 17^h 45^m, 75° west meridian time.

An intense occurrence of sporadic E-region ionization is illustrated in Figure 24. This should be compared with Figure 9 which shows the normal condition at the same time of day, a few days earlier. Normal penetration-frequency for the E-region can be seen, but instead of penetrating through to the F_1-region as is ordinarily the case at this critical frequency, the height of reflection drops back to within about 10 km of E-region levels. There is little change in height up to the highest frequencies, and on no frequency can the upper regions be seen. This indicates that the ion-density in the region must have exceeded 10^6 equivalent electrons per cc. In the early afternoon of the day of this observation, normal reflections were observed above the critical frequency for the *E*-region until about 15^h (75° west meridian time) after which strong reflections were observed from the *E*-region on successively higher and higher frequencies, progressively obliterating the echoes from regions F_1 and F_2. By 17^h no upper-region echoes could be observed, and not until 22^h had conditions returned to normal.

Because an *E*-critical frequency can usually be seen in the presence of this sporadic ionization, there appears little doubt that the effect ordinarily occurs just above the normal level of *E*-region maximum ion-density. As the effect decays, reflections from the upper regions become stronger and stronger, indicating that they can be seen through the sporadic ionization by a process of partial reflection.

The manner in which partial reflection from the *E*-region occurs is not well understood. Both during the decay of sporadic, intense *E*-region ionization and often during intervals when it is entirely absent, reflections from the level of the *E*-region of small intensity can be observed at frequencies well above the *E* critical frequency. Ordinary theory of partial reflection does not seem to account for the effect over such wide frequency-range. As a consequence, one is led to the view that the *E*-region is "cloudy" under such circumstances, in the sense that the density varies in the horizontal plane. The sporadic ionization in itself may be just a very large "cloud" of ions of greater density, for there is evidence that sporadic ionizations are localized over a relatively small area (perhaps a few square miles or a few hundred square miles) at a particular time. That such "ion-clouds" actually exist in the *E*-region is evidenced by sporadic reflections of very brief time-duration on the higher frequencies and from virtual heights varying from 100 to 300 km or so. These can be seen upon close examination in the records reproduced elsewhere in this paper. In all probability, these come in at an angle, rather than from overhead, because of varying direction of the ion-gradient associated with such "clouds."

While sporadic intense *E*-region ionization may occur at any time of the day or night, it appears to come most frequently in the early evening hours at Washington and Watheroo, though information on this point is not too certain. It appears predominantly in local summer at both Washington and Watheroo, being relatively infrequent in local winter. Observations show the effect to be much more frequent at Watheroo than at Huancayo—in fact over a period of about a year it occurred only 6.3 hours at Huancayo and about 70 times this total duration at Watheroo.

Harang [1030] has made an investigation of this effect at Tromsö, where it occurs repeatedly. He makes two points of interest. Sporadic *E*-region ionization often coincides with appearance of intense auroral activity. It has frequently coincided with small but distinct magnetic movements at Tromsö on otherwise quiet days. This point is best illustrated in Figure 25 after Harang, who says concerning it:

> The registrations of terrestrial magnetism indicate very quiet conditions for so highly a disturbed place as Tromsö—only a small disturbance occurring at 22^h 15^m middle European time. The disturbance is accompanied by a strong increase in ionization in the level of the E-layer. The maximum value for the electron-density in the E-layer level appears during the first phase of the disturbance when the deflection of the horizontal intensity is moderate. During the maximum deflection of the horizontal intensity the electron-density is decreasing—an effect which has been noted several times during the appearance of *small* magnetic storms.

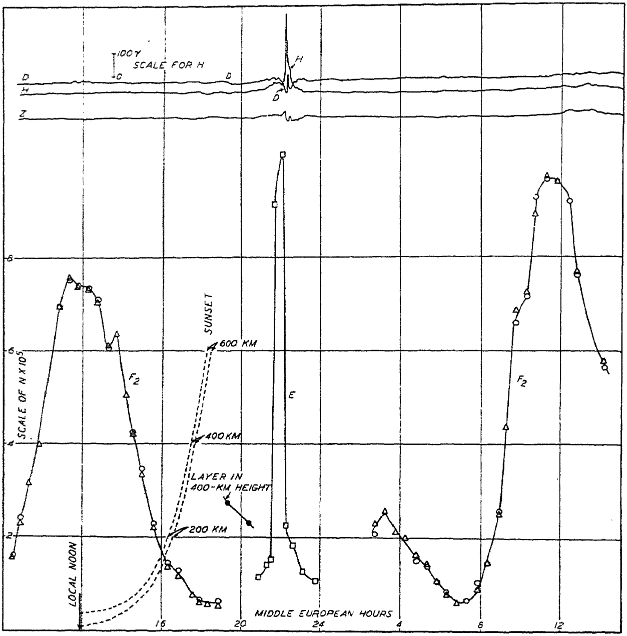


FIG. 25.—Coincidence of sporadic E-region ionization with small magnetic disturbance at Tromsö (*after Harang*).

It appears that a detailed study of this effect will prove exceedingly productive of ideas which will aid in understanding terrestrial magnetic and

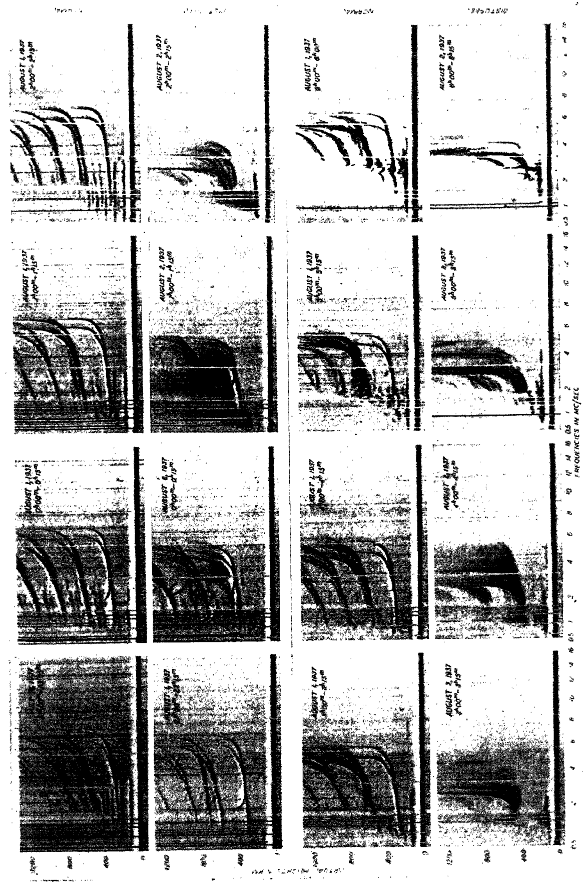


FIG. 26.—Ionospheric records, Kensington Experimental Station, during magnetically undisturbed and moderately disturbed conditions on summer night (showing effect of disturbance which began on August 1 about 17^h, becoming more pronounced about 22^h, 75° west meridian time, and continuing through the night).

auroral effects. The facts that Huancayo [978], at the magnetic equator, is relatively free from these sporadic E-region disturbances and that these disturbances there seem to increase in frequency and intensity to the north and south strongly suggest their source in bursts of ionized particles which are deflected in the Earth's magnetic field.

XII. IONOSPHERIC EFFECTS COINCIDING WITH MAGNETIC STORMS

Though as yet little understood, ionospheric changes coinciding with magnetic storms are perhaps the most interesting phenomena with which we have to deal. With the advent of magnetic disturbances, the most notable change usually occurs in the F_2-region, but there are associated effects in the lower regions. As has been mentioned, fluctuation of noon value of F_1 critical frequency is seldom more than ±5 per cent on undisturbed days. On days of magnetic disturbance, the value of maximum ion-density for the F_1-region decreases to values which may be 15 per cent or more below normal [977]. Although the effect is sharply defined in summer, it is more difficult to isolate in winter at a temperate-zone station because the F_1- and F_2-regions are merged and the F_1- critical frequency is not well defined.

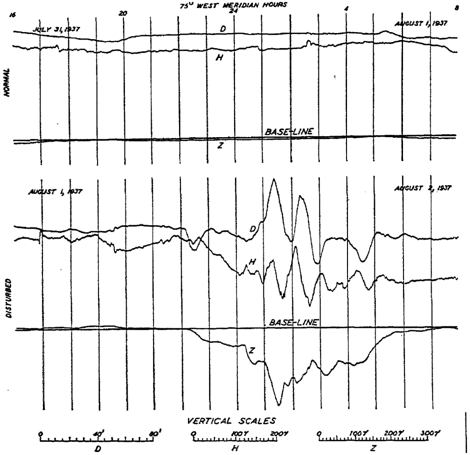


FIG. 27.—Magnetic records, Cheltenham Magnetic Observatory, showing magnetic conditions corresponding to ionospheric conditions of Figure 26.

Effect of magnetic disturbance in the F_2-region is usually much more pronounced, though not necessarily so [1053]. The best description of the effect must be given by the records themselves. In Figure 26 are compared records from the Kensington Experimental Station of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington for a disturbed night in early August and for the undisturbed night just preceding it. The magnetograms for these intervals are shown in Figure 27, the disturbance becoming pronounced about 22^h. During the disturbance the critical frequency for the F_2-region is greatly reduced. This means a corresponding reduction of ion-density at level of maximum, though not necessarily a reduction in the total ionization of the region. At the same time, the minimum virtual height of the F_2-region is greatly increased during the disturbance. This is especially pronounced as morning is reached, when the F_2-region, instead of separating from the F_1-region as is normally the case, appears over the edge of the F_1-region at a great height. Several investigators have suggested that this may mean that the F-region is abnormally heated during the magnetic storm.

The effects at night, illustrated in Figure 26, are more or less typical of all nights during which magnetic disturbances occur. At the onset of the disturbance the two magneto-ionic components near the penetration-frequency become less and less clearly defined, until they cannot be distinguished at all. Retardations from varying equivalent height begin at a relatively low frequency, above which there is a wide band of frequencies on which reflections come from almost any random height, bounded only by a relatively sharp lower limit. As these conditions develop, one can often see two, three, or more complete pairs of critical penetration-frequencies which rise from the F-region curve at widely different frequencies. The interpretation of these effects is not entirely clear, but it seems probable that the region becomes more and more diffuse. At the same time it loses its normal horizontal homogeneity and becomes "cloudy." Thus waves penetrate at different frequencies, depending upon whether they go through or between the "clouds" of ions, and as a consequence reflections are returned at one frequency for many different virtual heights. The dimensions of, and the space between, such clouds must be of the order of several wave-lengths to permit such an interpretation. Under such conditions, the waves are reflected not only from overhead, but in all probability from points well off to the side, because the gradient of ionization is not necessarily normal but may have any random direction.

Effects during a disturbance commencing during the early morning hours of a midsummer day, and extending into the daylight hours, are shown in Figures, 28, where they are compared with the effects on the previ-

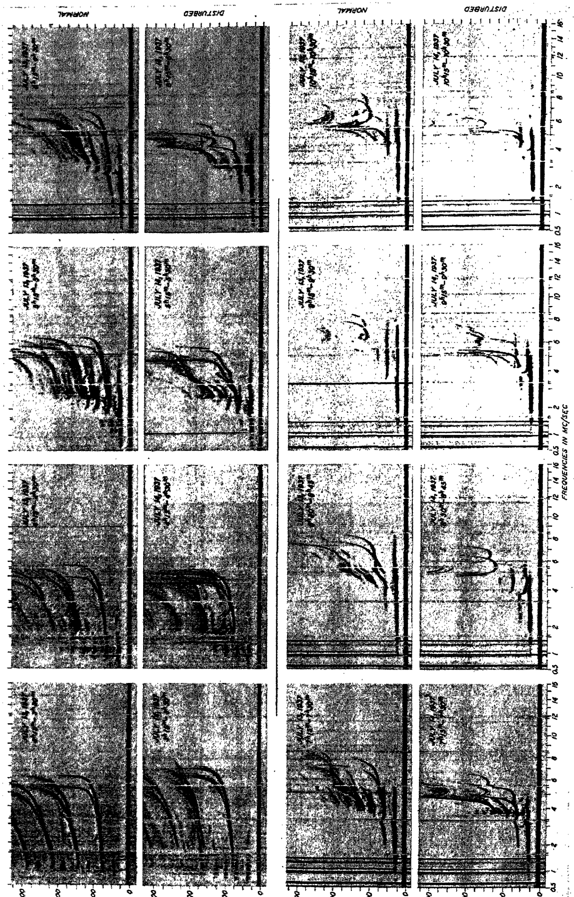


FIG. 28-A.—Ionospheric records, Kensington Experimental Station, during magnetically undisturbed and moderately disturbed conditions on summer morning (showing effect of disturbance which began on July 13 about 16^h, becoming more pronounced on July 14 after 3^h, 75° west meridian time, and continuing through day).

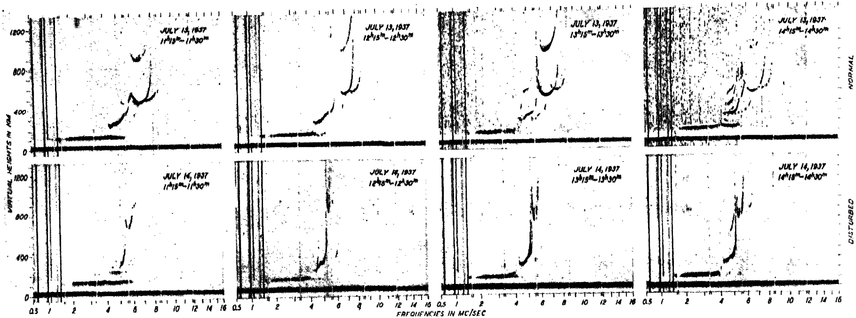


FIG. 28-*B*.—Ionospheric records, Kensington Experimental Station, during magnetically undisturbed and moderately disturbed conditions on summer midday (showing continued effect during day of disturbance which began on July 13 about 16h, becoming more pronounced on July 14 after 3h, 75° west meridian time, and continuing through day).

ous undisturbed day. In the daytime the F_2 critical frequency is so low that the F_2-region can be seen only over a narrow range of frequency just above the F_1 critical frequency. On some occasions, the ion-density of the F_2-region is so reduced during magnetic disturbance that it falls below the value of maximum ion-density in the F_1-region when the F_2-region cannot be seen at all for intervals up to several hours. With the reduction of critical frequency the virtual height becomes abnormally great. This is partly because of retardation of the wave at frequencies near the F_1 critical frequency, and partly because of a real increase in height. This is an extension of the effect shown toward the end of Figure 26.

If one makes a similar investigation during midwinter, the night effect coinciding with the magnetic disturbance is about the same as that for midsummer (see Figs. 29). The daytime effect with small magnetic disturbances is much less pronounced, usually evidenced only by a slight decrease of maximum ion-density at the most. In some cases an F_2 critical frequency somewhat above normal is observed. With the more intense disturbances, the effect becomes more like that observed during midsummer. On the basis of this evidence alone, one might suppose that the effect extended downward into the F_2-region only when it was high, as in midsummer, or at night, and that the effects coinciding with magnetic storms did not reach down to the lower F-region during winter midday, unless the disturbance was of the more intense type. It may be eventually shown that this is the case, though the effect of absorption which will be discussed later indicates a somewhat more complex picture.

The tendency for the correlation between magnetic disturbances and daytime values of F_2 critical frequency to change with season has been remarked upon by Appleton, Naismith, and Ingram [960] who have obtained correlation-coefficients at noon for data from Slough and from Tromsö during the International Polar Year of 1932–33. They find that the correlation is positive near midwinter and negative near midsummer, the coefficients being larger for Tromsö than for Slough. They also find that on days of small activity the correlation is positive, changing to negative as the activity increases. Because magnetic storms are irregular in occurrence, it has been a matter of chance whether anyone would be observing when one commenced, and so it is impossible to find enough data associated with moderate and large disturbances to permit classification and generalization concerning these events.

Increased absorption of the radio wave during magnetic disturbance is quite pronounced. Reflections become much weaker, and the number of multiple reflections is decreased. In extreme cases, reflections become so weak that they are difficult to detect. Because of the change of heights and critical frequencies of the regions during the magnetic disturbances, it is not easy to determine the region in which the principal absorption

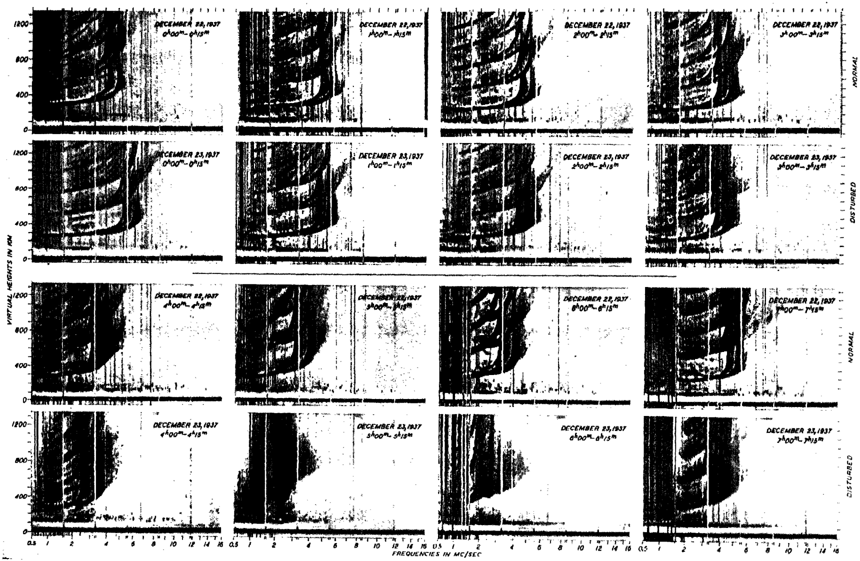


FIG. 29-A.—Ionospheric records, Kensington Experimental Station, during magnetically undisturbed and moderately disturbed conditions, on winter day [showing decreasing effect of disturbance as daylight conditions set in (disturbance began in early morning of December 23 about 3h 75° west meridian time)].

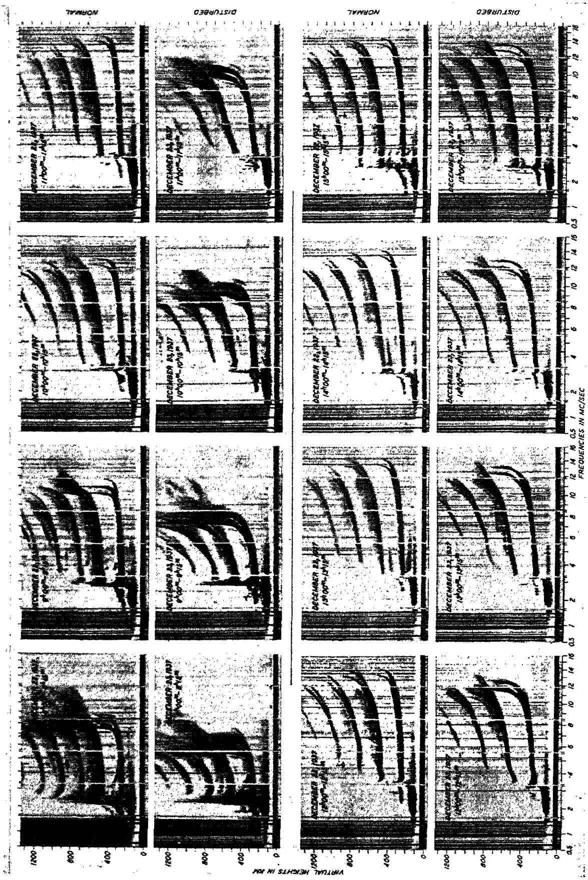


FIG. 29-B.—Ionospheric records, Kensington Experimental Station, during magnetically undisturbed and moderately disturbed conditions on winter night (showing development and effect of disturbance which began on December 23 about 3^h, 75° west meridian time).

occurs. Appleton has pointed out that sporadic *E*-region ionization sometimes occurs at the onset of the disturbance (see Fig. 25), followed by increased absorption, and suggests that this absorption is due to the extension downward of the increase of ionization to the lower *E*-region which as a consequence becomes an absorbing region. It seems probable that this is the case during some disturbances, particularly of the polar type. Such an explanation also accounts for the increase in the intensity of very long radio waves over long paths which is sometimes observed during magnetic storms. However there are many cases of increased absorption with magnetic disturbance without the appearance of sporadic *E*-region ionization, and one cannot be sure that this explanation can be generally accepted for all cases.

One of the most interesting effects can be seen most clearly from Figure 26. This shows the development of a magnetic storm-effect in the F_2-region at night. The magnetic storm became pronounced about 22^h as can be seen from the trace. With the increase of magnetic activity, the effect becomes apparent in the F_2-region almost immediately, in spite of the fact that the observations were made in the night hemisphere. This evidence indicates the presence of a powerful disturbing agency inducing this change with the associated magnetic effect in the dark hemisphere. One is strongly tempted to look for the cause in the effect of charged particles shot into the atmosphere and deflected into the dark hemisphere by the Earth's magnetic field.

XIII. SCATTERED REFLECTIONS

The records of most normal nights and of most normal winter days show the appearance of echoes from great heights at frequencies higher than the critical frequency for the F_2-region. These echoes, which have been called "scattered reflections" [1051], appear to be an extension of the second multiple reflection; that is, the echo which must have traversed the path four times with an intervening reflection at the Earth. The most probable source of such echoes is from a point in the ionosphere which is not directly overhead, but somewhat to one side, so that the total path is longer than if the echo came from directly overhead. One explanation offered by T. L. Eckersley involves refraction in the *F*-region and intervening reflection upward again from a "cloudy" *E*-region [1441]. This is probably the case for a part of such echoes, but those which are closely associated with the height of the second multiple must somehow be associated with reflection at the ground. Such reflections must indicate a tilt in the gradient of the *F*-region from the normal, as must be the case over a distance from east to west owing to change in ionization with time or a "cloudy" condition near the maximum ion-density of the F_2-region.

XIV. REFLECTIONS OF SHORT RETARDATION

The recent investigations of Colwell and Friend [1002] and of Watson Watt [1114] and his associates have disclosed the presence of echoes of very short retardation corresponding to distances ranging from somewhat less than a km up to 60 km or more. Examples of such reflections from an equivalent height of about 50 km may be seen in Figure 29, where they appear just above the base-line. The technique best adapted to the ionospheric investigations described in this paper is not well suited to observation of echoes having a retardation equivalent to a height less than about 45 km. Measurement of lower heights requires a much shorter pulse and an amplifier with a wide-band characteristic. In dealing with the high dispersion of the upper regions, critical frequencies are very poorly defined if this kind of technique is used. Therefore the equipment for measuring echoes of short delay is in turn not adapted to ordinary ionospheric measurements. As a consequence, investigations of these short-delay echoes requires an essentially different technique, and only when they come from equivalent distances of about 45 km or more can they be seen as in Figure 29 by means of the usual methods.

The question arises whether such echoes occur because of ionic reflection in the atmosphere of the nature we have been discussing. The investigators mentioned above have been inclined to attribute them to this source. However, there seem good reasons to believe that such echoes are not reflections from ion-banks in the lower atmosphere and, therefore, that their appearance does not indicate the presence of lower atmospheric ionization of great density. The matters which must be considered in this connection are these. (1) There is as yet no evidence that the reflections are coming from overhead, or from high angles. It is not improbable that they come from discrete objects on the Earth, either directly, or over paths involving ordinary atmospheric refraction connected with temperature-inversions or other meteorological effects. The fact that such echoes are best seen at the higher frequencies strongly implies such an explanation. (2) Though echoes of very short retardation are reported as quite regular phenomena, those of somewhat longer retardation, as in Figure 29, are irregular, occurring only a few days per month. Such irregularity may well be associated with the special meteorological conditions required under (1). In the same way, the presence of thunder-storms or other similar effects of weather may well be associated with such other meteorological effects as may produce the bending in the lower atmosphere as necessary to bring new reflectors on the ground into range. Therefore, observation of unusual echoes during thunder-storms is not a sufficient condition to establish ionic reflection. (3) Direct observation of ionization in the lower atmosphere by manned and unmanned sounding balloons indicates an ion-density which is about 10^{-8} too small to produce ionic reflection [631]. (4) When such echoes are present, as in Figure 26, the normal echoes from the upper regions seem unaffected in intensity, though a strongly ionized lower atmospheric region interposed below them should produce an enormous absorption. (5) The energy required to maintain such ionization in the lower atmosphere under normal recombination-processes is tremendous, and appears to exceed that which we imagine can be present under ordinary conditions. (6) The technique of observation with very short pulses is exceedingly difficult, and extraneous pulses of varying amplitude due to distortion of circuit and pulse are difficult to prevent. Thus it is not impossible that some extraneous echoes may be produced in the equipment itself. Therefore, until these matters are thoroughly canvassed, it appears best not to place too much dependence on the idea that such echoes arise from intense ionization in the lower atmosphere.

XV. RÔLE OF IONIZED REGIONS IN RADIO TRANSMISSION

The relative importance of the various regions in supporting high-frequency radio transmission is of especial interest. Although the complete theory is rather involved and lengthy, it is desirable to introduce the more fundamental ideas in simple form. Resultant expressions are only approximate but serve as an introduction to consideration of propagation over long distances. Because it is possible to delineate structure of layer at vertical incidence in the form of curves of virtual height versus wave-frequency, already given, propagation-conditions over long distances can best be derived directly in terms of these curves.

The index of refraction in the ionosphere was found in Section IV (neglecting the effect of the Earth's magnetic field) to be given by

$$\mu = \sqrt{1 - Ne^2/\pi m f^2} \tag{9}$$

where f is the wave-frequency. At normal incidence the condition for reflection is that $\mu = 0$, so that

$$Ne^2/\pi m = f^2 \tag{10}$$

We define this quantity determined from f at normal incidence as $Ne^2/\pi m \equiv f_N^2$. For each value of f_N on the ionospheric record, we have a corresponding virtual height. Then equation (9) becomes

$$\mu = \sqrt{1 - (f_N^2/f^2)} \tag{11}$$

This expression again involves the assumption that the Lorentz polarization-correction is zero. If the value $\frac{1}{3}$ is used, the expressions have the same general form and lead to the same general conclusions, but the numerical results are altered materially. From Snell's law for refraction,

$$\mu_i \sin \delta = \mu \sin r \tag{12}$$

where μ_i and μ are refractive indices in the medium of incidence and refraction and δ and r the angles of incidence and refraction, respectively. In general, μ_i is substantially unity and $r = 90°$ for any angle of incidence if the wave is to be returned to Earth. Then, from equations (11) and (12),

$$\mu = \sin \delta = \sqrt{1 - f_N^2/f^2} \tag{13}$$

From simple trigonometric transformation, we have the relation

$$f = f_N/\cos \delta \tag{14}$$

which relates the wave-frequency propagated at any angle of incidence (δ) to the wave-frequency that will be reflected at the same value of ion-density (and therefore the same point in the ionosphere) at vertical incidence. This is sometimes referred to as the secant-law.

If propagation is assumed over a flat Earth, the angle of incidence at the medium is identical with the angle of propagation, so that only the ionization-density (and not the height) of the reflecting regions is involved. However, such an assumption can be used only over very short distances. For such short distances the angle of incidence is near zero, where $\cos \mu$ departs from unity very slowly. Thus, propagation from the ionosphere over very short distances is essentially the same as at normal incidence.

For distances of more than a few km, the curvature of the Earth must be taken into account; for, because of it, the angle of incidence at the layer will be less in general than the angle of departure from the ground. From the law of sines, the angle of incidence is related to the angle of departure by the expression

$$\sin \delta = [r/(r + h)] \sin \alpha \tag{15}$$

where α is the angle of departure with respect to the normal, r is the radius of the Earth, and h is the real (not the virtual) height of the region. Then, to a good degree of approximation*

$$\cos \delta = (\sqrt{r \cos^2 \alpha + 2h})/(\sqrt{r + 2h})$$

where (h^2/r) is neglected as very small compared with either r or h. From this, equation (14) becomes

$$f = f_N\sqrt{(r + 2h)/(r \cos^2 \alpha + 2h)} \tag{16}$$

Thus, propagation over the curved Earth is dependent both upon the density of ionization and upon the real height of the layer. It must be noted here that in the case of the curved Earth, the Breit-Tuve equivalence theorem no longer holds, for it assumes independence of angle of incidence with respect to height, a condition only true over a flat Earth.

---

* This expression is good to within one per cent of the exact expression for virtual heights up to 500 km, and for tangential propagation. For other conditions the error will be smaller, approaching zero for either lower heights or smaller angles of departure.

The real height of reflection is involved in equation (16), and the distinction between real height, h, and virtual height, h', must be known for exact computation of propagation over a distance. Conversely, given simultaneously the time-retardation of echoes over a distance and at vertical incidence at the center of the reflection path, the relation between h and h' can be determined—an experiment that has not yet been performed.

In considering propagation in the ionosphere there are three principal questions to be raised, namely: (1) What is the highest frequency that can be propagated from a given layer without regard to the distance at which the echoes can be observed? (2) What is the performance of a given frequency over different distances? (3) What is the performance of different frequencies over a given distance?

To determine these exactly would require accurate knowledge of the difference between real and virtual heights at all frequencies and would require, also, inclusion of the force and direction of the Earth's magnetic field along the wave-path in the ionosphere. We are interested in this treatment, however, in the general form of the results, and for this purpose we shall assume the real and virtual heights to be equal. This is substantially correct for the E-region, but less certain for the F-regions, especially near the penetration-frequencies. It will be shown, however, that the range of wave-frequencies close to the penetration-frequency leads only to an echo of secondary importance so that failure of the assumption here is not serious.

The highest wave-frequency that can be propagated from a given region will leave the Earth nearly tangentially, so that equation (16) becomes

$$f_M = f_N\sqrt{(r + 2h)/2h} \tag{17}$$

when f_M is the upper limiting frequency at which echoes can be returned from a given ion-density, determined by f_N, and at height h. The frequency f_M is expressed only in terms of the heights of reflection of particular wave-frequencies, f_N, which are measured at vertical incidence. Therefore, curves for particular values of f_M can be plotted in terms of h and f_N, which are the quantities recorded on the ionospheric trace. This is done in Figure 30 where the curves are superimposed on typical ionospheric traces. To interpret Figure 30, consider the intersection of a particular curve of f_M, with the ionospheric trace. The portion of the trace to the right of the intersection (that is, toward higher frequencies) represents the ionospheric regions that will support propagation back to Earth on wave-frequency f_M over an appropriate range of distance; reflection from the ionospheric regions represented by the trace to the left of the intersection is impossible. Thus, in the upper trace of Figure 30, no reflection from the *E*-region is possible for wave-frequencies above 18 mc/sec, while in the lower trace 10 mc/sec is the highest wave-frequency that can be reflected. Information obtained so far indicates a variation of noon summer-maximum critical frequency for the *E*-region of about 3.5 to 4.4 mc/sec at Washington from minimum to maximum of sunspots.

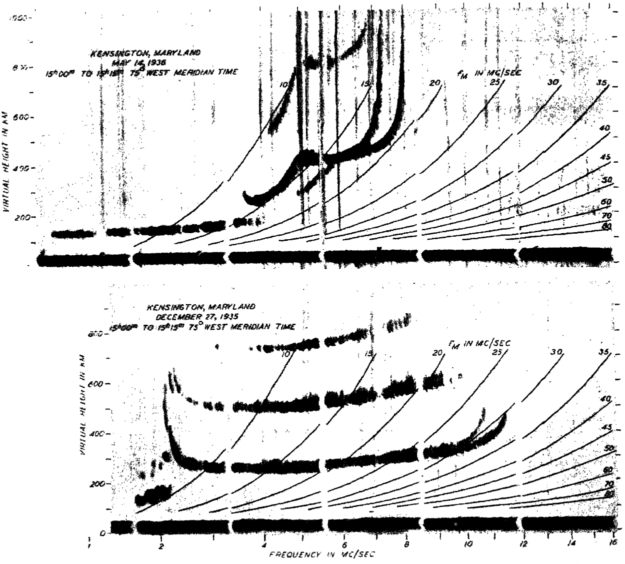


FIG. 30.—Graphical method of determination of maximum sky-wave frequency (f_M).

Thus, a corresponding variation between about 19 to 24 mc/sec in maximum frequency returned from the *E*-region can be expected under these circumstances. Likewise, corresponding limitations can be determined from the diurnal and seasonal curves given earlier.

It has been mentioned that sporadic *E*-region ionization occasionally occurs, and in Figure 24 an example is given where *E*-region is seen up to about 14 mc/sec. This value being entered on Figure 30, it is seen that such ionization at the point of reflection would support reflection of wave-frequencies up to about 80 mc/sec over appropriate distances. It is this sporadic E-region ionization which accounts for occasional phenomenal reports of very long distance transmission by radio amateurs on ultrahigh wave-frequencies such as 60 mc/sec (5 meters).

Because of the decrease of angle of incidence with respect to height, a much higher density of ionization is required to support reflection on a given wave-frequency from the F-region than from the E-region at oblique incidence. For this reason, as illustrated in the upper trace of Figure 30, the F_1-region does not enter into long-distance propagation nearly so importantly as does the F_2-region. This will be seen better from subsequent analysis. At night, only the F-region is effective in reflecting all but the very low frequencies (below about 1,500 kc/sec), where the E-region returns echoes at the longer distances. An exception occurs in the case of sporadic E-region ionization given above.

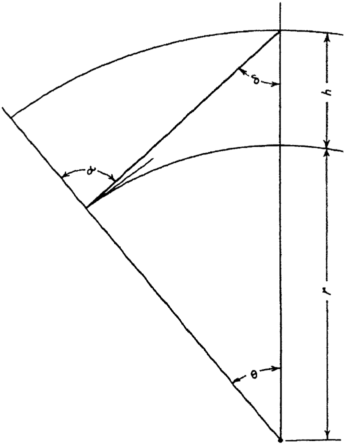


FIG. 31.—Relation of angle of departure, α, to angle of incidence, δ, and displacement, θ.

The second case to be considered is the performance of a given wave-frequency over different distances.

The lateral displacement of the wave-group in regions below the level of reflection is neglected implicitly with the assumption previously made that virtual and actual heights were the same. Then, from simple geometry (see Fig. 31),

$$\alpha = \delta + \theta \qquad (18)$$

where θ is the angular displacement around the Earth to the point of reflection.

From (15)

$$[(r + h)/r] \sin \delta = \sin (\delta + \theta) \tag{19}$$

The linear displacement, d, to the point where echoes are received will be $2r\theta$; substituting equation (13) and applying suitable trigonometric transformations, we have

$$d = 2r[\{\sin^{-1} [(r + h)/r]\sqrt{1 - f_N^2/f^2}\} - \cos^{-1} (f_N/f)] \tag{20}$$

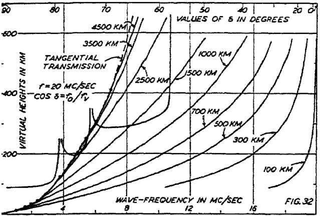
For particular values of f, this expresses the distance in terms of the two quantities given on the ionospheric trace, namely, f_N and h. As before it is possible to superimpose the curves for d computed from equation (20) for a particular frequency on the ionospheric trace. The intersections with the ionospheric trace describe the propagation on the selected frequency for different distances.

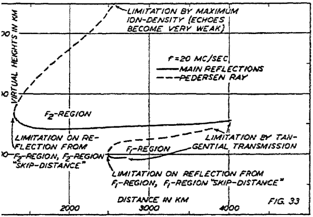
This is illustrated in Figure 32 in which equation (20) has been used to compute curves of f_N versus height for the frequency of 20 mc/sec corresponding to different distances. The limitation for one-step transmission given by the dashed curve is identical with the curve for 20 mc/sec given in Figure 30. These curves are superimposed on a typical ionospheric trace. For ionospheric conditions given by this trace, no intersections occur for distances less than 1,150 km, so that no transmission via the ionosphere is possible at distances between 0 and 1,150 km. This is the "skip-distance" on 20 mc/sec for the ionospheric conditions assumed. Intersections occur over the distance-range of 1,250 to 4,000 km, and therefore one-step transmissions are possible over this frequency-range. These intersections are plotted in Figure 33, which shows the effective reflecting region over the various distances.

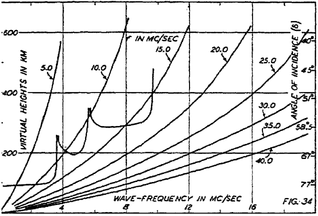
It will be seen that for the shorter distances a pair of echoes are returned from each region and at each distance from different heights. These correspond to the two intersections with the ionospheric trace near the penetration-frequency. The lower reflection of the pair is much stronger as evidenced by the strength of multiple reflections on the ionospheric traces in the region of this intersection. The second or upper is the long-path or so-called "Pedersen" ray and is returned from regions very close to the level of maximum ion-density. It is ordinarily the weaker echo.

The skip-distance depends directly, not upon the value and height of the maximum ion-density of the region, but upon a value somewhat below this level. Thus the 1,150-km curve is tangent to the ionospheric trace at about 10.2 mc/sec, or about 0.6 mc/sec below the penetration-frequency. Only the Pedersen ray is returned for values of f_N above the point of tangency of the skip-distance curve, so that the main reflection is not affected by the rapid curvatures near the penetration-frequency of the ionospheric trace. The long-distance limitation on one-step transmission is of course identical with the 20 mc/sec curve in Figure 30.

Greater distances are, of course, covered on this wave-frequency for the ion-distribution shown by two or more steps of transmission. In this case, the curve for the fraction of the distance covered by each step must be selected, and the ionospheric trace representative of conditions at the apex of each step must be selected. Thus, certain restrictions on propagation may be introduced in each step. Likewise, conditions governing higher-order reflections may be examined in the same way, though it will be seen that the simple multiple relationship between reflection-heights is lost at angles below the vertical. Furthermore, higher-order echoes from a given region can occur only provided that the distance covered by the "multiple" is greater than the shortest skip-distance determined from the conditions at the different apices of the several multiples.







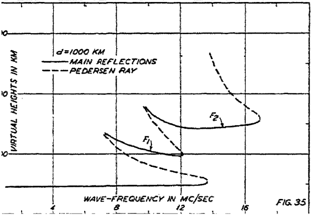


Fig. 32.—Example of determination of propagation-conditions for $f = 20$ mc/sec from typical ionospheric record.

Fig. 33.—Example of determination of propagation-conditions for $f = 20$ mc/sec deduced from ionospheric conditions shown in Figure 32.

Fig. 34.—Example of determination of propagation-conditions on various wave-frequencies for $d = 1{,}000$ km from typical ionospheric record.

Fig. 35.—Propagation-conditions on various wave-frequencies for distance $d = 1{,}000$ km deduced for one-step transmission with ionospheric conditions shown in Figure 34.

For wave-frequencies such that the curve for limiting frequency shows F_1-region transmission possible, there will be echoes from both F_1- and F_2-regions over a certain distance-range (usually, the longer distances).

This range of distance is usually much narrower than that covered by the F_2-region and ordinarily is entirely, or almost entirely, overlapped. Exceptions to this occur during magnetic storms and in the northern summer during sunspot-minima, when the F_2-region ion-density is low and the height is high. In this case, curves for the F_2-region such as shown in Figure 33 fall behind those for the F_1-region, so that the F_2-region becomes entirely ineffective in propagation over all but very short distances.

The third case is the performance of different wave-frequencies over a given distance. In this case, equation (20) can again be used and curves for different values of wave-frequency, f, may be computed in terms of f_N and h, d being held constant.

Such curves are shown as an example in Figure 34 for distance 1,000 km, where they are superimposed on a typical ionospheric trace. The same method of intersection can be used as before to determine propagation-conditions. In this case, the curve for 17 mc/sec becomes tangent to the trace for the F_2-region (at about 9.4 mc/sec) so that a point at distance 1,000 km will be in the skip-zone for all higher frequencies. Again the Pedersen ray appears above the level of tangency of the curve and trace at commencement of skip-distance for each region. In Figure 35 is shown the plot of intersections that give the propagation-conditions for $d = 1{,}000$ at the various frequencies for one-step propagation.

When transmission takes place along a portion of the curves of Figure 35 where dh/df is very small (as along the long flat portions), transmission should be good with regard to quality. On the other hand, if transmission is in a region where dh/df is large (as near the skip-frequencies), the dispersion of different wave-frequencies is large. As a consequence, different side-bands of the transmission, corresponding to discrete audio frequencies, will be reflected from materially different heights. Thus the relative phases of the audio-frequency components will be displaced from their original relation, and distortion will be evident. This is often observed just before a high-frequency radio broadcast program fades out as the point of reception passes into the skip-zone because of changing ionic density at and near the level of reflection.

The discussion just given has been designed only as an introduction to the underlying basis of radio-wave propagation in the ionosphere. It will be appreciated that with the wide variations experienced in the distribution of ionization with time of day, season, year, and latitude—which have been illustrated earlier—it is here impossible to outline individually the different conditions experienced by radio services widely distributed with regard to wave-frequency used and distance-coverage desired. The methods indicated, however, can be applied to most conditions experienced, to the degree of approximation that has been made in their derivation, to gain some concept of the ionospheric regions that are important in particular problems of propagation.

The commencement of continuous automatic observation of the ionosphere using multifrequency methods ushers in a new epoch in the history of ionosphere-research. Though we have met continually with lack of decisive information concerning vital points, such data are now accruing by the new, more complete methods. We can confidently expect a more complete solution of many of the problems which have been discussed as investigation of the new data goes forward.

CHAPTER X

THE UPPER ATMOSPHERE

E. O. HULBURT

Naval Research Laboratory

I. THE METEOROLOGY OF THE UPPER ATMOSPHERE

(1) WIND-MIXING AND DIFFUSION IN THE UPPER ATMOSPHERE

The atmosphere from sea-level to about ten km above sea-level is known as the "troposphere" and from about 10 to 20 km as the "stratosphere." The region above 20 km extending outward to interplanetary space may be referred to as the "upper atmosphere." The troposphere is approximately in adiabatic or convective equilibrium. Swift winds keep the gases thoroughly mixed, so that except for water-vapor the composition of the atmosphere is the same throughout the troposphere to a high degree of approximation. The temperature decreases with the height to about 220°K at 12 km. From about 12 to 20 km the temperature is observed to remain about 220°K, the diurnal variation being less than 1°. In this region the average wind-velocity is less than in the lower levels. Above 20 km there are few observations. Wigand [1447] in 1930 succeeded in sending two sounding balloons to a height of 33 km. The temperature was found to increase gradually from 219°K at 20 km to 226°K at 33 km. Measurements of the brightness of the twilight sky have shown that the temperature of the atmosphere in the temperate zone under conditions of twilight was 219 ± 15°K from 20 to 60 km throughout the year [1466]. Meteor trains at heights from 30 to 110 km, often persisting for many minutes, were observed to drift and to be violently distorted, indicating air-currents and eddies in these levels of velocities greater than 100 km hr^{-1}. The fading and variability of radio signals indicate movements of the atmosphere in levels from 100 to 300 km above sea-level.

The effect of wind-mixing on the composition of the high atmosphere was first worked out by Maris [1058]. We give here only the essential physics of his calculation; the complete details would be too long. If the temperature were constant and if there were no winds, the atmosphere would be in isothermal equilibrium. In such a state the number, n, of molecules cm^{-3} of each component gas at a height z cm above sea-level is given by

$$n = n_0 e^{-pz} \tag{1}$$

n_0 being the molecular density at $z = 0$, that is, sea-level.

$$p = mg/kt \tag{1a}$$

where m is the mass of the gas molecule, g the acceleration of gravity at the height z, t the absolute temperature, and $k = 1.372 \times 10^{-16}$ erg deg^{-1}, the molecular gas-constant. Since p is smaller for the lighter gases than for the heavier ones, it follows from (1) that n for the lighter gases decreases less rapidly with increasing z than for the heavier ones. Therefore the proportion of the light gases in an isothermal atmosphere is greater at the greater heights.

If the atmosphere is uniformly mixed, the proportions of all gases are the same at all heights.

Assume now that the atmosphere is at a constant temperature, t, at all times, that it is first uniformly stirred up by winds, and that it is then kept entirely free from winds while diffusion and gravity work to restore the isothermal equilibrium condition. The lighter gases diffuse upward and the heavier ones downward. The rate of diffusion increases with z and hence the isothermal distribution is attained most rapidly in the high levels and more slowly in the low levels. The level where the region of complete diffusion joins the region of complete mixing is termed the "diffusion-level." Maris showed that for helium, for example, the diffusion-level was established at 150 km in 0.53 day; after one day it descended to 146 km, after two days to 140 km, after five days to 136 km, after a year to 110 km. The diffusion-level varied with the gas and with the temperature. On the assumption that diffusive separation has progressed for five days the diffusive levels for various gases and temperatures are given in Table 1. The assumption of five days is of course not very certain, but changing the time from one day to 30 days would not shift the diffusion-levels more than 30 km. Anyhow, the diffusion-level

TABLE 1.—*Diffusion-levels of atmospheric gases*

Gas	Temperature			
	350°K *km*	300°K *km*	260°K *km*	220°K *km*
H_2	157	146	133	114
H	151	140	127	111
O_2	147	134	120	106
A	145	131	118	104
CO_2	145	131	118	104
Kr	143	130	116	102

is not sharply marked for it is merely a region of transition between regions of complete and zero diffusive separation of the atmospheric gases.

The amounts of oxygen in the atmosphere up to 29 km, of helium up to 21 km, and of nitrogen up to 18.5 km have reeently been determined from samples of air obtained in high-altitude balloon flights [1476, 1495, 1498, 1502, 1510]. It was found that the proportions by volume of the respective gases were constant within a few per cent at all heights reached. The results were therefore in support of the foregoing diffusion-calculations. However, deviations from constancy, small, variable, and real were observed; these appeared to be attributable to irregularities in the lower atmosphere such as weather.

(2) THE TEMPERATURE OF THE UPPER ATMOSPHERE

The temperature of the atmosphere to great heights cannot be calculated with certainty. To do this would require more exact data than are available at present of the amounts of the atmospheric gases at all levels and their absorption-coefficients for light throughout the optical spectrum. Dissociation, chemical combination, and ionization of the molecules and atoms will be involved in the thermal balance. Calculations of various effects of radiative warming and cooling have been given by Maris [1058], Gowan, and others [794, 1453].

Carbon dioxide, water-vapor, and ozone are important in regulating the temperature of the atmosphere below 150 km, because of their infrared bands, and ozone is particularly important because of its ultraviolet band from 2,900 to 2,300 Ångstroms. All the bands absorb energy from the Sun during the day and the infrared bands radiate energy at night. The temperature which results depends on the relative rates of absorption and emission and these in turn depend to a large extent on the distribution of ozone. Ozone is known to exist [1241, 1444, 1491] mainly above 20 km and, if it is assumed that ninety-nine one-hundredths of the ozone is in the region from 20 to 60 km and the remaining one one-hundredth is distributed in fixed proportion through the higher levels, the day temperatures above 70 km rise above 350°K and the night temperatures descend to 220°K. If less ozone were assumed at great heights, the day temperatures would remain high and the night temperatures would be increased. This is due to the relatively high values of the absorption of the ultraviolet band of ozone and to the low absorption of the infrared bands. Thus, even though the ozone is very thin it can trap considerable energy from the sunlight and heat the atmosphere during the day, and because of the weak infrared absorption it cannot radiate away much of the energy during the night.

The high levels above 160 km are warmed by molecular oxygen which absorbs solar energy in virtue of its ultraviolet band from 1,800 to 1,300 Ångstroms. The molecular absorption-coefficient β is defined by

$$i = i_o \epsilon^{-\beta n'} \tag{1b}$$

where i_o is the original intensity of the light and i is the intensity after passing through n' oxygen molecules. From spectrograms [1479] in the Schumann region β may be estimated to average 10^{-17} across the oxygen band. With the solar constant 1.35×10^6 erg cm^{-2} sec^{-1} and extrapolating the solar spectral-energy curve into the ultraviolet, assuming that the Sun radiates as a black body at 6000°K, the energy in the region from1,800 to 1,300 Ångstroms falling into the atmosphere is 10^3 erg cm^{-2} sec^{-1}. With these values and with the distribution of molecular densities of Table 3 it is found that during the day the temperature of the atmosphere in levels from 160 to 300 km rises about 50°K per hour. What temperature will actually obtain cannot be determined in the absence of knowledge of the cooling processes. Probably convection and wind-stirring of the hot gases above 200 km into the lower levels cause the cooling.

We may sum up the situation thus: Calculations based on reasonable hypotheses indicate that the high atmosphere is warm during the day but do not show whether it remains warm or grows cool during the night.

Radio, however, has furnished some evidence. It is an observed fact that the heights of the E- and F_1-regions of ionization remain fairly constant during the day, night, and season in tropical, temperate, and polar latitudes (see Section II for further details). The maximum ionization of the E-region remains at 110 km within 15 km and of the F_1-region at 220 km within 20 km. This means that the average temperature of the atmosphere below about 200 km probably does not fluctuate so much as 30°K with the day and night; for if the average fluctuation were greater than 30° the layers would rise and fall by amounts greater than those observed. Above 220 km in the F_2-layer, radio indicates pronounced diurnal temperature-changes.

The result is that as a working hypothesis we adopt the temperatures for the daytime atmosphere from sea-level to 220 km which Maris derived for a "summer day." The temperatures are given in Table 2. It seems reasonable to think that the night temperatures are below the day values.

TABLE 2.—*Temperature, t, of the day atmosphere*

z, km	t, °K	z, km	t, °K
0	287	60	260
10	220	80	320
20	225	100	360
30	230	200	360
40	240	220	360

(3) MOLECULAR DENSITY OF THE ATMOSPHERE TO GREAT HEIGHTS

From Table 1 the diffusion-level of the gases of the atmosphere may be taken to be at 150 km for a temperature of 360°K. Therefore at levels below about 150 km the constitution of the atmosphere is constant and the proportions of the various gases, with the exception of ozone, are the same as at sea-level. The total molecular density, n, in this region was determined step by step from (1) and (1a), with t from Table 2 and with $m = 4.78 \times 10^{-23}$ gram, the mass of the average air-molecule at sea-level. From n and the sea-level proportions of the gases the molecular densities up to 150 km were calculated. These are given in Table 3 for the more abundant gases. The table was continued above 150 km for each gas by means of (1) and (1a) with m for the gas. n was then calculated at each level by summing up the molecular densities for the individual gases.

Although a small amount of hydrogen, about one part in 10,000 by volume, is in the lower atmosphere, it is believed that there is no free hydrogen in the upper atmosphere chiefly because no hydrogen lines are observed in the spectrum of the aurora and of the night sky. As far as can be guessed the conditions aloft are such that hydrogen if present would occasionally emit its characteristic radiations. Further, Kaplan [1472] was able to produce in the vacuum-tube nitrogen radiations similar to those of the aurora but was able to do so only when all trace of hydrogen had been removed.

There is another effect to be considered, the dissociation of molecular oxygen and nitrogen to atoms. Such atoms exist, for it is known that the

TABLE 3.—*Molecular densities of the gases of the atmosphere*

z, km	N_2	O_2	A	CO_2	He	Total
0	2.0×10^{19}	5.4×10^{18}	2.4×10^{17}	7.7×10^{15}	1.0×10^{14}	2.6×10^{19}
20	1.5×10^{18}	4.0×10^{17}	1.8×10^{16}	5.7×10^{14}	7.1×10^{12}	1.9×10^{18}
40	8.4×10^{16}	2.3×10^{16}	1.0×10^{15}	3.2×10^{13}	4.3×10^{11}	1.1×10^{17}
60	7.8×10^{15}	2.1×10^{15}	9.4×10^{13}	3.0×10^{12}	4.0×10^{10}	9.9×10^{15}
80	8.0×10^{14}	2.2×10^{14}	9.6×10^{12}	3.0×10^{11}	4.1×10^{9}	1.0×10^{15}
100	1.2×10^{14}	3.3×10^{13}	1.5×10^{12}	4.6×10^{10}	6.3×10^{8}	1.6×10^{14}
120	2.0×10^{13}	5.4×10^{12}	2.4×10^{11}	7.7×10^{9}	1.3×10^{8}	2.6×10^{13}
140	3.5×10^{12}	9.3×10^{11}	4.2×10^{10}	1.3×10^{9}	1.8×10^{7}	4.4×10^{12}
160	6.1×10^{11}	1.5×10^{11}	5.3×10^{9}	1.5×10^{8}	5.6×10^{6}	7.7×10^{11}
180	1.1×10^{11}	2.2×10^{10}	4.8×10^{8}	1.0×10^{7}	4.4×10^{6}	1.4×10^{11}
200	2.2×10^{10}	3.3×10^{9}	4.5×10^{7}	7.5×10^{5}	3.5×10^{6}	2.5×10^{10}
220	3.2×10^{9}	5.1×10^{8}	4.4×10^{6}	4.7×10^{4}	2.8×10^{6}	3.7×10^{9}
240	5.3×10^{8}	7.8×10^{7}	4.1×10^{5}	3.6×10^{3}	2.2×10^{6}	6.1×10^{8}
260	8.7×10^{7}	1.2×10^{7}	3.9×10^{4}	2.9×10^{2}	1.8×10^{6}	1.0×10^{8}
280	1.4×10^{7}	1.8×10^{6}	3.6×10^{3}	2.3×10	1.4×10^{6}	1.7×10^{7}
300	6.4×10^{6}	2.8×10^{5}	3.3×10^{2}	1.8	1.1×10^{6}	7.7×10^{6}
350	2.6×10^{4}	2.6×10^{3}	....	....	7.1×10^{5}	7.3×10^{5}
400	....	....	....	....	4.1×10^{5}	4.1×10^{5}

green line in the aurora and the light of the night sky originate from the oxygen atom. The calculation of the previous section indicated that the temperature of the atmosphere above 160 km rises about 50°K per hour during the day, owing to the absorption of solar ultraviolet light by molecular oxygen. The temperature soon becomes so high that oxygen molecules, and probably nitrogen molecules, are dissociated to atoms. On the assumption that the dissociation occurs above 200 km the values of n are much greater than those of Table 3. This is shown in Table 4; column 2 of Table 4 is the same as the last column of Table 3; column 3 is calculated on the assumption that above 200 km oxygen is atomic, and column 4 on the assumption that both oxygen and nitrogen are atomic; the temperature is 360°K in all cases. If the atmosphere of column 2 is changed to that of columns 3 and 4 there is an expansion of the atmosphere such that, for example, the molecular density at the 250-km level of the atmosphere of column 2 is at 280 and 330 km for the atmospheres of columns 3 and 4, respectively.

TABLE 4.—*Molecular densities of the atmosphere*

z, km	With molecular oxygen and nitrogen	With atomic oxygen	With atomic oxygen and nitrogen
200	2.5×10^{10}	2.9×10^{10}	5.1×10^{10}
250	2.5×10^{8}	8.4×10^{8}	6.4×10^{9}
300	7.7×10^{6}	7.0×10^{7}	8.3×10^{8}
350	7.3×10^{5}	7.0×10^{6}	1.0×10^{8}
400	4.1×10^{5}	1.0×10^{6}	1.3×10^{7}

It is convenient to express the molecular densities of Table 3 analytically as a function of z. Denote the total molecular density by n. Plotting log n against z gives a line which although curved may be regarded approximately as made up of two straight lines, one from $z = 0$ to 80 km and the other with a slightly different slope from 80 to 300 km. Therefore, we write

$$n = n_0 \cdot \exp(-pz) \tag{2}$$

where, for z in cm, p is 1.26×10^{-6} below 80 km and 0.872×10^{-6} above 80 km.

The free-path, γ, of a particle of diameter σ is

$$\gamma = 1/\sqrt{2}\pi n\sigma^2 \tag{2a}$$

From Table 3, at 220 km, $n = 3.7 \times 10^9$. At this height γ is of the order 10^2 km for a molecule of $\sigma = 3 \times 10^{-8}$ cm and increases rapidly with the height. The total number of molecules, $\bar{n}$, above a level, z, is

$$\bar{n} = \int_z^\infty n dz \tag{2b}$$

and from (2)

$$\bar{n} = n/p \tag{2c}$$

From (2c), above 220 km there are 10^{16} molecules cm^{-2}; these experience 10^{14} collisions sec^{-1} at the 220-km level. Approximately 10^{16} molecules of $\sigma = 10^{-8}$ cm will just fit into an area of one cm^2. Therefore, above 220 km there are few collisions and the values given in Table 3 above this level, which were based on assumptions of kinetic gas-equilibrium, have little meaning. The actual molecular densities are probably much greater than those of Table 3, for the 10^{16} molecules and many more below them dance up and down, receiving upward thrusts from thermal impacts below and falling back under gravity. This is the outer fringe of the atmosphere.

(4) WINDS IN THE UPPER ATMOSPHERE

The movements of meteor-trains have yielded direct information about the air-currents in levels up to 110 km. Barnard [1429] was perhaps the first observer to reach a definite conclusion. In the case of six trains he found that there was an easterly motion of the train at night no matter what the direction of the flight of the meteor. Trowbridge [1518] and Kahlke [1471] assembled a list of 74 meteor-train observations in the years from 1741–1916; 20 of the trains were observed in the day and 54 at night, all in the Northern Hemisphere. The daylight trains occurred in levels from about 30 to 80 km and showed on the whole a westerly drift, indicating an east wind; 18 of the daylight trains were seen in the late afternoon and two at about noon. The night trains occurred in levels from about 30 to 110 km and showed roughly a prevailing easterly movement, indicating a west wind.

The rate of drift of the meteor-trains in degrees or miles was recorded in 26 cases and indicated winds and eddies of velocities of over 100 km an hour, in two cases of nearly 200 km an hour. All the trains were immediately twisted and distorted as if by atmospheric currents and turbulence.

On the theoretical side some very simple notions may be stated. If the atmosphere in levels above 30 km is a few degrees warmer during the day than at night, there will be winds blowing from the day to the night areas, hence a northward flow of the upper air in the daylight Northern Hemisphere. But, if nothing interferes, north-moving air-currents swing to the east because of the Earth's rotation and become a west wind. In the Southern Hemisphere the flow is southward, also swinging to the east to become a west wind. At the same time if there are prevailing westerly winds in certain portions of the high atmosphere, there would probably be easterly winds at lower levels, for the air must flow back somewhere. These rather sketchy theoretical inferences agree with the meteor-train observations. However, further observations are necessary before the air-circulation in the high atmosphere can be said to be known and understood.

(5) THE PROPAGATION OF SOUND-WAVES THROUGH THE ATMOSPHERE TO GREAT DISTANCES

It is observed that the sound of explosions or cannon fire, or any source of considerable intensity, may be heard at great distances up to several hundred km with, however, regions of silence. Around the source there is a region of audibility of radius about 50 to 100 km which gives way to a region of silence from 50 to 200 km in width. This in turn is often surrounded by a second zone of audibility. The forms of the zones are apparently affected somewhat by winds and other meteorological conditions. Figures 1 and 2 give some of the results obtained at Lindenburg, Germany [1460], from explosions set off during the midday hours of May 3, 1923, and December 18, 1925, respectively. The small black dot in the figures is the location of the explosion, the shaded areas are the zones of audibility, and the unshaded areas the regions of silence. The time for the sound to reach various distances was measured and found to be longer than that for propagation over the surface of the Earth. These facts indicated that a portion of the sound-waves travels upward into the high atmosphere and is bent back to the Earth again. Wegener has written a good survey of the subject in the "Lehrbuch der Physik" [1432, 1456, 1520]. Hergesell and Duckert [1460] give a bibliography of 176 references.

The explanation of the zones of audibility and silence is based on the refraction of the sound-waves by the atmosphere. The velocity of sound in a gas is approximately proportional to the square root of the absolute temperature and independent of the pressure. Some of the waves emitted by the source spread out over the surface of the Earth, becoming weaker by absorption until they are lost; they give rise to the first zone of audibility. Rays leaving the source at angles inclined to the horizontal are bent upward, because the temperature of the atmosphere decreases with altitude for the first ten km. From 10 to 20 km the temperature is approximately constant and the rays are straight. Somewhere above 20 km the temperature increases and the rays are bent over and descend to the Earth in the second zone of audibility. Here they may be reflected and make another excursion into the high levels to descend again to the third zone. Actually the zones are not always sharply marked and the regions of silence may not appear. Cases were found in which the direct overland sound-rays, the so-called "normal" rays, reached into the second zone of audibility, so that a single emitted pulse of sound was received as two pulses separated by an interval of 50 sec or more, the first pulse being due to the normal ray and the second pulse to the overhead ray.

Observations of the air-waves from gunfire have been made systematically in England since 1927. The times for the sound to travel to the

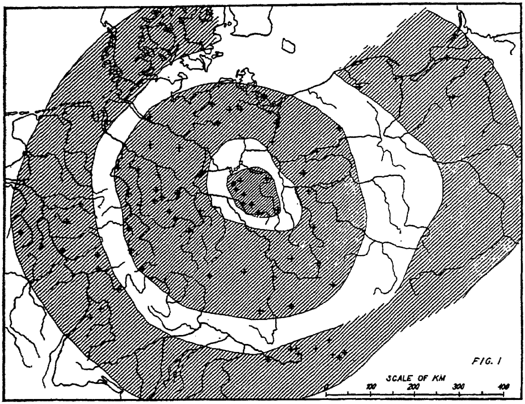


FIG. 1

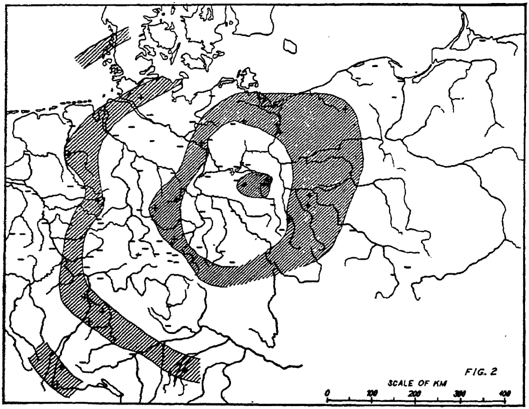


FIG. 2

FIGS. 1 and 2.—Zones of audibility (shaded) and of silence (unshaded) of the sound from explosions set off on (1) May 1, 1923, and (2) December 18, 1925 (*after Hergesell and Duckert*).

second zone of audibility, about 200 km, and the angles of descent of the waves into the zone were measured [1521]. On the assumption of a uniform increase of temperature with altitude setting in at about 30 km Whipple [1521] calculated what temperatures were necessary to account for the times of transit of the sound and the angles of the down-coming rays as observed during daylight hours of the months from May to September in the years 1928–30. The temperatures came out around 280°K at 40 km and 350°K at 55 km. If the level where the temperature-increase sets in were placed at 50 km, a more rapid gradient of temperature would be necessary to account for the observations. The data indicated higher temperatures in July than in May or September but were on the whole too few to bring out the seasonal variation with certainty. There are no observations at night. Such observations are in view, however, and under the direction of the Commission for the Investigation of the Waves from Explosions of the International Meteorological Organization one may expect interesting and valuable experimental results.*

II. THE IONOSPHERE

(1) THE THREE IONIZED REGIONS OF THE HIGH ATMOSPHERE

The atmosphere above about 80 km is heavily ionized; the region is known as the "ionosphere." The ionosphere is of fundamental importance in radio-wave propagation for it reflects radio waves back to Earth. If it did not exist, radio signaling to distances beyond several hundred km would be impossible by present methods. Early investigations of the ionosphere were made by means of the radio-echo method [992], the skip-distances of short radio waves [1104], and the interference of the downward-reflected radio wave [951]. The radio-echo method yields by far the most detailed information about the ionization overhead and has been used in many recent investigations. In the earlier experiments two regions of ionization were observed with maximum density of ionization at about 100 and 200 to 400 km; these were designated as the *E*- and *F*-regions, respectively.

The first convincing proofs of the upper ionization given in the 1926 papers [951, 992, 1104] were followed by many experiments in England [956], Germany [1452, 1506], the United States [1089, 1090], and elsewhere. Although much was learned about the variations in the *E*- and *F*-layers with the time of day, season, and magnetic activity, it appeared that long-continued measurements at a number of stations over the Earth would be necessary to bring to light all the facts. Such a program was entered upon in 1931 by the National Bureau of Standards, the Bell Telephone Laboratories, and the Department of Terrestrial Magnetism of the Carnegie Institution of Washington with stations at Washington, D. C., United States, at Deal, New Jersey, United States, at Huancayo, Peru, and at Watheroo, Australia. Results are available in a series of papers [976, 977, 1017, 1050, 1051, 1054, 1092, 1115, 1450, 1451] which may be regarded as a first approach to a world-wide survey of the ionosphere. The data are presented in detail in the following pages. They show that in the daytime for solar altitudes above about 50° the F-region divides into two regions, F_1 and F_2, the F_1-region being at about 200-km and F_2 at 250- to 350-km virtual heights. At night F_2 and F_1 join to form a single F-region at about 250 km.

---

* Whether the Commission now functions is not known.

(2) THE RADIO-ECHO METHOD OF BREIT AND TUVE

In the radio-echo method a transmitter is arranged to emit a sharp pulse of radio waves which are received by a receiver a short distance, 0 to 30 km, away. If the wave-length is suitable, two or more pulses are received although only one pulse was transmitted. The first pulse arrives at the receiver after direct transit over the ground, the so-called "ground-wave" or reference-wave. The second and following pulses are those which have traveled upward into the high atmosphere and have been reflected back to Earth again by the ionization. These are the echoes. The time for the echo to return multiplied by the velocity of light gives the equivalent optical distance in vacuum which the pulse has traveled and hence the virtual height of the ionization above sea-level. If the wave-length is decreased, echoes continue to be received until a wave-length is reached, termed the "critical" wave-length, beyond which a change occurs. The waves shorter than the critical wave-length either do not come back at all or return after a longer time-interval than those greater than the critical wave-length, showing that they have penetrated through the ionization and either have passed away to space or have been reflected by a higher-lying region of ionization. Thus the echoes provide a means of measuring the height and the density of the ions in each region of ionization.

To derive the formulas used in radio-echo sounding we consider the general case of the propagation of a radio wave in a magnetized ionized gas, the direction of propagation being at an angle to H, the magnetic field of the Earth. Resolve H into components H_1 in the direction of propagation and H_2 perpendicular to this direction. Let y be the number of electrons per unit volume. e is the charge and m the mass of the electron; λ is the wave-length of the radio wave, and c is the velocity of light in vacuum. All quantities are expressed in CGS EMU. Following the classical electron theory of Lorentz [1478] we assume no restoring force on the electrons due to the medium, no absorption, and no effect of the electrons on each other; this amounts to placing a, f, and g equal to zero in equations (198) [1478]. Discussion by Tonks and Darwin [1003] has shown, however, that for the ionosphere $a = 0$ is correct. The solution of the equations of motion of the electron shows that the medium is doubly refracting and that the wave is split into two elliptically polarized waves [945, 991, 1033] of refractive indices, μ, given by

$$\mu^2 = 1 + 2/\{2(p - 1) - q_1^2/p \pm \sqrt{(q_1^2/p)^2 + 4q_2^2}\} \tag{3}$$

where

$$\begin{aligned} p &= 1 - 1/\sigma\lambda^2 & \sigma &= ye^2/\pi m \\ q_1 &= 1/\sigma\lambda_1\lambda & \lambda_1 &= 2\pi cm/H_1e \\ q_2 &= 1/\sigma\lambda_2\lambda & \lambda_2 &= 2\pi cm/H_2e \\ & H^2 = H_1^2 + H_2^2 \end{aligned} \tag{4}$$

By an analogy, none too good, with doubly refracting crystals, the ray of refraction given by (3) with the positive [+] sign is often referred to as the "ordinary" ray and by (3) with the negative [−] sign as the "extraordinary" ray.

For $H = 0$ we have $\gamma_1 = \gamma_2 = 0$ and (3) reduces to

$$\mu^2 = 1 - \qquad /\pi m \tag{5}$$

which is the classical expression in the absence of a magnetic field. For γ_2 and γ_1 in turn equal to zero (3) reduces, as it should, to the equations given by Lorentz [1478] and by Taylor and Hulburt [1104] for propagation parallel and perpendicular, respectively, to H.

The condition for total reflection of the wave is that $\mu = 0$, and the critical wave-length is determined by putting $\mu = 0$ in (3) and solving for λ. Denoting the critical wave-lengths from (3) with the plus [+] and minus [−] signs, respectively, by λ_p and λ'_p, it is found that

$$\lambda_p = 1/\sqrt{\sigma} \tag{6}$$

and

$$\lambda'_p = 2\lambda_0/(\sqrt{1 + 4\sigma\lambda_0^2} \mp 1) \tag{6a}$$

where

$$\lambda_0 = 2\pi cm/He \tag{6b}$$

With $H = 0.3$ gauss, as at the equator, $\lambda_0 = 357$ meters; with $H = 0.5$ gauss, as in temperate latitudes, $\lambda_0 = 214$ meters.

It is seen from (6*a*) that there are two values of λ'_p for the extraordinary ray. However, the ray can have only one state of polarization at any height and that value of λ'_p will appear for which μ first reaches zero. This will be for the greater value or for λ'_p given by (6*a*) with the minus [−] sign. λ'_p from (6*a*) with the plus [+] sign can thus not occur and is not found physically.

It is noteworthy that the critical wave-lengths depend through λ_0 and (6*b*) on H, and not on the components of H_1 and H_2, and are therefore independent of the direction of propagation of the waves with respect to H. A more complete discussion would consider absorption; however, the foregoing formulas are approximately correct for small absorption.

From (4), (6), and (6*a*) with the minus [$-$] sign

$$y = \pi m/e^2\lambda_p^2 \tag{7}$$

$$y = (\pi m/e^2)(1/\lambda_p'^2 + 1/\lambda_0\lambda_p') \tag{7a}$$

where y is the maximum value of the electron-density in the region of ionization, the maximum being taken for y varying with z, the height above sea-level. These expressions, and primarily (7), are the basis of the measurement of y for any region of ionization at any time by an observation of λ_p or λ_p'. It is surprising that (7) is the same as the critical wave-length expression derived from (5) in the absence of a magnetic field; such a simplification was perhaps unanticipated.

It is often convenient to use the critical frequencies, f_p, f_p', and f_0, where

$$f_p = c/\lambda_p, \qquad f_p' = c/\lambda_p', \qquad f_0 = c/\lambda_0 \tag{8}$$

Then from (6), (6*a*), and (6*b*) it follows that $f_p^2 = f_p'^2 \pm f_0 f_p'$, or

$$f_p = f_p'\sqrt{1 \pm f_0/f_p'} \tag{9}$$

For short radio waves, those for which $\lambda < 100$ meters, f_0/f_p' is small compared to 1 and to a first approximation (9) becomes

$$f_p' - f_p = \pm f_0/2 \tag{9a}$$

Putting (4) and (6*b*) into (9*a*) yields

$$f_p' - f_p = He/4\pi m \tag{10}$$

For ions λ_0 is 10^3 to 10^4 times longer than the usual radio wave-lengths, the exact value depending on the mass of the ion as seen from (6*b*). Thus, if the ionization is made up of ions, the region is not appreciably doubly refracting. The refraction is given by (5); there is only one critical frequency, $f_p^2 = \pi mc^2/ye^2$; and in general the formulas for the non-magnetized medium hold to a close approximation.

Therefore, if two critical frequencies related by (10) are observed, it is clear evidence that the region under observation is predominantly electronic as far as its refraction of radio waves is concerned. If only one critical frequency is observed, the first inference is that the region is largely ionic, although there is the possibility that the region is electronic and that the other critical frequency existed but was lost by absorption. Furthermore, to say that the electrons are sufficiently numerous to control the refraction of radio waves does not mean that the electron-density, y_e, is necessarily greater than the ion-density, y_i. It means merely, from (5), that $y_e/m_e > y_i/m_i$, m_e and m_i being the electron- and ion-masses, respectively; or, since m_i/m_e is of the order 10^4, that $10^4\, y_e > y_i$. Thus there may be 3×10^5 electrons and 10^9 oxygen ions in a cc and the refraction be still predominantly electronic.

The measured time for the radio echo to return multiplied by the velocity of light, c, gives the equivalent optical distance to the height reached by the radio ray. This is the virtual height, z'. The true height, z, attained by the ray is in general less than the virtual height, for the velocity of the pulse is the group-velocity which for an ordinary dispersive medium is μc and hence less than c. If as the radio frequency, f, of the pulse is increased, z' remains fairly constant, the ion-gradient in the region of ionization is high and z' is pretty close to z. If z' increases with decreasing f, the ion-gradient is not so rapid and z' may be considerably greater than z. As f nears f_p, very great values of z' are often, but not always, observed. These matters are fully discussed in a number of articles [976, 977, 1017, 1050, 1051, 1054, 1092, 1115, 1450, 1451] based on earlier papers by Breit [991, 1435]. Typical (f, z')-curves obtained at Huancayo, Peru, are shown in Figure 3 [from Fig. 2, 977].

In any region of ionization y increases with z to a maximum value. The value of z at this height is called rather loosely the "height of the region above sea-level." Above this y ceases to increase for a space.

The quantity obtained directly from experiment is f_p or λ_p and from these the maximum value of y is derived in terms of electrons or ions from (7) and (8) with the appropriate values of e and m. Since it is not known what the ions are, we may keep our ignorance in view by assuming that the atmospheric ion is singly charged with $m = 3.7 \times 10^{-23}$ gram which is the average mass of a nitrogen molecule and an oxygen atom. m for the electron is 9×10^{-28} gram and hence for refraction of radio waves one electron is equivalent to $(3.7 \times 10^{-23}/9 \times 10^{-28}) = 4.1 \times 10^4$ ions or to 2×10^4 ion-pairs on the assumption of equal densities of positive and negative ions. Then the relation between the maximum-in-height ionization, y, of any region and the critical wave-length or frequency of the region for the ordinary ray is from (7) and (8)

$$y = 1.12 \times 10^{13}/\lambda_p^2 = 1.24 \times 10^{-8} f_p^2 \tag{11}$$

where y is in terms of electrons cm^{-3}, λ_p in cm and f_p in cycles sec^{-1}, and

$$y = 2.2 \times 10^{17}/\lambda_p^2 = 2.5 \times 10^{-4} f_p^2 \tag{11a}$$

where y is in terms of ion-pairs cm^{-3}.*

---

* In the following sections the experimental data of the ionosphere are presented as equivalent electron-densities, y, and references are given as though the various experimenters had actually obtained the data. The experimenters, however, have done no such thing. They have in reality measured the critical frequencies, f_p, and have left it to the present author to calculate y from f_p by means of (7) or (7*a*), on the idea possibly that f_p is a wholesome experimental fact and y an unwholesome theoretical quantity. The author refuses to be criticized for attributing y to the experimenters. He takes the view that y is just as good an experimental quantity as f_p, or that f_p is just as bad a theoretical entity as y. He accuses the experimenters of being theorists when they measure f_p; he prides himself on being an experimenter when he uses y.

(3) THE E-REGION

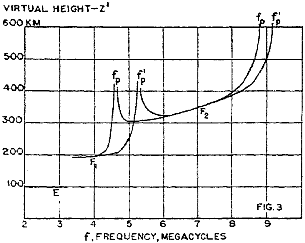
The virtual height, z', of the E-region has been measured in various parts of the United States [1017, 1050, 1051, 1054, 1089, 1090, 1092, 1450, 1451], in England [957], Germany [1452, 1506], Peru [976, 977, 1115], India [1519], Northern Russia [986], Alaska, Antarctica, Norway [1030], and North-East Land [1117]. The observations may be summarized by the statement that the height of the E-region is between 100 and 140 km with small seasonal, diurnal, and latitudinal variations. z' at Huancayo [1115] was about 100 km, at Washington [1017] 110 to 120 km, in England [1118] 125 to 140 km in winter and 100 to 110 km in summer. Approximately, z' of E is 100, 120, and 140 km for solar zenith-angles 0°, 60°, and 70° to 80°, respectively. There is evidence [1118, 1509] of a slight stratification of the E-region, for at times there is a minor maximum of ionization at about 105 km. Echoes interpreted as being reflected from ionization at 140 to 180 km, between the E- and F_1- or F-regions, have occasionally been noticed [1017, 1089, 1090, 1509].

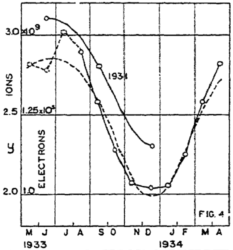
In the (f,z')-curves for the E-region (see, for example, Fig. 3), z' is approximately constant for $f < f_p$. This means that the real height, z, is but little less than z' and that the ionization sets in fairly sharply at the lower boundary of the region. Exact calculations cannot be made from the data available but it may be estimated that y decreases by a factor of 5 in at least the first ten km below the maximum of y.

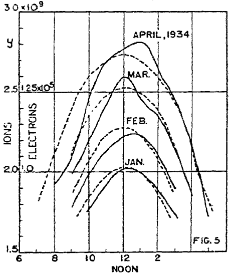
Magnetic splitting of the echoes from the E-region has been rarely observed in the United States or at Huancayo. In some experiments in England the magnetic separation was observed [1499]. Measurements in England and Australia of the polarization of 400-meter waves descending from the E-region indicated the presence of some electrons [964, 1454]. Thus, experiment as yet has not determined whether the E-region is predominantly electronic or ionic; this uncertainty is reflected in Figures 4 to 7 which give y in terms of both ions and electrons. It may turn out perhaps that for certain latitudes, times of day, etc., the E-ionization is mainly ions and in other cases electrons.

In Figures 4 and 5 are shown the diurnal and seasonal changes in y for the E-region as calculated by means of (11) and (11a) from a year's observations of f_p at Washington [1017]. In Figure 4, which gives the noon values averaged over the days of a month, the points for June, July, and August, 1933, were based on fewer data and were less accurately determined than the points for the other months. Day-to-day values varied as much as 20 per cent showing, as might be expected, that the upper atmospheric ionization is changeable within limits. For comparison, the values for 1931 [977] are plotted in Figure 4.

In Figure 5 are given four of the 12 diurnal curves [1017] from August, 1933, to September, 1934, of the hourly values of y at Washington averaged over the days of the month. In Figure 6 the hourly values of y from all the 12 months [1017] are plotted against the zenith-angle, ζ, of the Sun, the morning values being separated from the afternoon values. The crosses in Figure 6 were from the curves of June, July, and August, 1934, and are less accurate than the dots which refer to the period September, 1933, to April, 1934. It is seen in Figures 5 and 6 that the values of y are symmetrical on either side of noon within experimental error, the maximum of the ionization occurring within an hour of noon. The dotted curves of Figures 4, 5, and 6 are proportional to $\sqrt{\cos \zeta}$, a relation derived from theory (see section III).







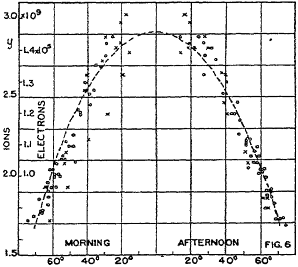


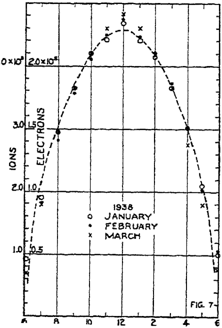
FIG. 3.—Typical (f, z')-curves at Huancayo, Peru (*after Carnegie Institution of Washington*).

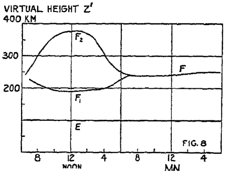
FIG. 4.—Monthly average noon E-ionization at Washington (after National Bureau of Standards) (dotted curve, y proportional to $\sqrt{\cos \zeta}$).

FIG. 5.—Hourly average E-ionization at Washington (after National Bureau of Standards) (dotted curve, y proportional to $\sqrt{\cos \zeta}$).

FIG. 6.—Hourly average E-ionization at Washington for a year plotted against zenith-angle, ζ, of Sun (dotted curve, y proportional to $\sqrt{\cos \zeta}$).

At night the E-region ionization is much less than in the day; it decreases during the night. At 2 o'clock at Washington [1051] f_p ranges from 0.6 to 1.6 × 10^6 cycles sec^{-1} or y from 1 to 6 × 10^8 ion-pairs cm^{-3} or 0.5 to 3 × 10^4 electrons cm^{-3}. Although the average E-ionization undergoes a fairly regular cycle of diurnal and seasonal variation, it is subject to sudden erratic increases [978] which may persist for a few minutes or an hour or more. During the changes y may increase to more than five times its normal value. The unusual E-ionization is on the whole local and not wide-spread. The size of the areas affected is not known; its occurrence at Washington does not extend to New York, and vice versa. The frequency of occurrence appears to increase with latitude, in temperate latitudes to be the greatest in summer, and to be more frequent in the afternoon and evening. Evidence from Huancayo, Peru, and Watheroo, Western Australia, indicates that the phenomenon is not directly associated with thunder-storms.





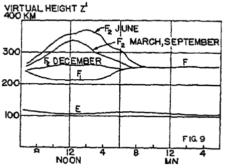


FIG. 7.—E-ionization at Huancayo (*after Carnegie Institution of Washington*).

FIG. 8.—Virtual height of the ionized regions at Huancayo, latitude 12° 03′ south (*after Carnegie Institution of Washington*).

FIG. 9.—Virtual height of the ionized regions at Washington, latitude 39° 46′ north (*after National Bureau of Standards*).

The (f,z')-curves at Huancayo (Fig. 3) show a characteristic difference from those at Washington. As f approaches penetration of the E-region, z' remains approximately constant, whereas in higher latitudes and for the higher regions of ionization at Huancayo z' increases rapidly as f_p is neared. Further, at Huancayo as f is increased above f_p and echoes from F_1- or F-regions begin to occur, echoes from E still persist but with lessening intensity, showing that part of the radio-echo energy has penetrated E and part has been reflected from E. Wells [1115] reasonably suggests that the effect is due to the absorption of frequencies near f_p of E, the absorption being greater at low than at high latitudes. Values of y for the E-region for the first three months of 1938 at Huancayo [1115] are given in Figure 7.

At Calcutta, India, echoes from a virtual height of about 55 km have been observed [1484], indicating ionization in which y was from 0.4 to 0.8×10^5. Evidence has been secured [1513] of relatively weak ionization at various levels below 100 km.

(4) THE F-REGION

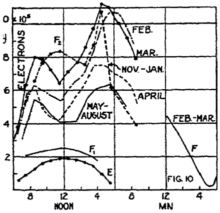
The ionization above about 180 km is known as the F-region. Magnetic splitting in accord with (10) of the radio echoes from the region usually occurs, showing that the ionization is predominantly electronic. During the day the F-region separates into two regions, F_1 and F_2, which at night coalesce to form a single F-region.* The average diurnal virtual heights, z', of the regions at Huancayo and at Washington are given in Figures 8 and 9. It is seen that z' of F_1 experienced small seasonal and diurnal variations, being approximately 210, 230, and 240 km for the solar zenith-angles, 0°, 60°, and 70° to 80°, respectively. In the case of z' of F_2, however, the seasonal and diurnal variations are large. At Washington z' was 350 to 400 km for summer noon and 250 to 300 km for winter noon; at Watheroo z' was much the same as at Washington with a six-month displacement in phase. Since Watheroo is at 30° 19′.1 south latitude, summer occurs there when it is winter in Washington. The maximum value of z was near noon at Watheroo, Huancayo, and Washington. For F_1, F_2, and F the (f,z')-curves slope upward with increasing f, so that the true height, z, may be considerably less than z', but probably not so much as 100 km less.

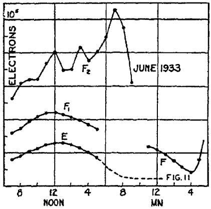
In Figures 10 to 14 are plotted the diurnal and seasonal values of the ionization-density at Huancayo [976, 977, 1115] and Washington [1017, 1051, 1054]; the E-region values in terms of electrons are also included; the figures give a fairly complete survey of the ionosphere. At Huancayo y for F and F_1 is fairly constant with the season; the F- and F_1-curves of Figure 10 are averages over the period from November, 1933, to August, 1934. As seen in Figure 10, there is a seasonal variation in y of F_2, y being on the whole greater during the southern summer, November to February, than in the winter May to August, although the actual value of y at any particular time may vary as much as 40 per cent from day to day. The F_2-curves (Fig. 10) show that y has an erratic and ragged maximum in the morning, a minimum near noon, and a higher maximum in the afternoon. y decreases through the night with occasional temporary increases of as much as 50 per cent. Sufficient observations are not available to determine whether the night increases have any regular distribution on the average.

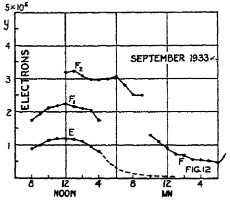
---

* The notation, F, F_1, and F_2, used here is that proposed by Kirby, Berkner, and Stuart [1051], the discoverers of the daytime bifurcation of the F-region, and adopted by the International Scientific Radio Union in September, 1935. F_1 and F_2 are the lower and upper strata, respectively, of the day F-region, and F is the night F-region. Thus F is ambiguous and means either the entire ionization above 180 km day and night with all the strata or the single-stratum night F-region.

The ionospheric observations at Washington are available in the form of monthly average curves of y for each hour of the day for each region during the year beginning with May, 1933; less detailed data extend back to 1931. In Figures 11 to 14 are given the y-curves for midsummer, midwinter, and equinox and in Figure 15 the monthly average noon values of y for F_1; in Figure 15 the points for May, June, and July were based on few observations and are given less weight than the other points.







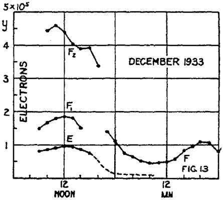
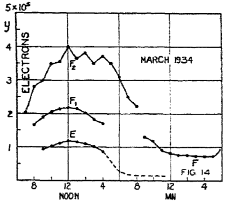


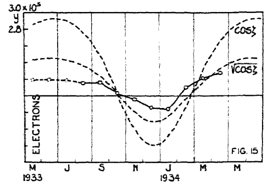
Fig. 10.—Ionization at Huancayo (*after Carnegie Institution of Washington*).
Figs. 11 to 13.—Ionization at Washington (*after National Bureau of Standards*).

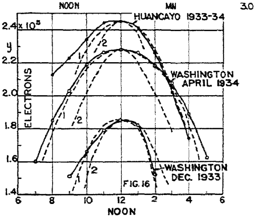
In Figure 16 y for F_1 is plotted on larger scale than in Figures 10 to 15. From the Washington data the following facts appear: (1) y for F_1 follows the Sun fairly regularly; it is greater in summer than in winter and is a maximum approximately at noon; (2) y for F_2 reaches a daily maximum of about 4 or 5×10^5 at noon, in the early afternoon, and around sunset in winter, equinox, and summer, respectively; (3) y for F decreases during the night, except on midwinter nights when, after diminishing during the early part of the night, it increases to a definite maximum between 2 and 4 o'clock and then diminishes again until the rise at dawn.

The data of Figures 4 to 15 were obtained during 1933–34, which was a period of sunspot-minimum and few magnetic disturbances. From the data the main world-wide features of the ionosphere during solar quiescence are as follows:

The E- and F_1-regions are fairly simple; they lie at about 100- and 200-km levels, respectively. The density of ionization of each is a maximum directly under the Sun and diminishes with increasing angle from the Sun, so that the E-region fades away in the night and the F_1-region is swallowed up on the twilight meridian by the descending F_2-region. The F_2-region is more complicated. It swells out toward the Sun, being 300 to 400 km away from the surface of the Earth at its most lofty point, and sinks back to a 250-km level in the twilight zone. Its density of ionization is always greater and more variable than that of the E- and F_1- regions. In tropical latitudes its density of ionization has two maxima, an irregular one around 10 o'clock and a larger, smoother one near sunset; in temperate latitudes there is a single maximum in winter near noon, and in summer there are two maxima similar to the tropical case except that often the morning maximum is ill-defined. During the night, apart from irregular ups and downs, the F ionization-density diminishes at all latitudes except for a recrudescence in the small hours of winter morning in temperate latitudes.







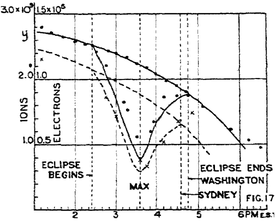


FIG. 14.—Ionosphere at Washington (*after National Bureau of Standards*).

FIG. 15.—Monthly average noon F_1-ionization at Washington (dotted curves, y proportional to $\cos \zeta$ and $\sqrt{\cos \zeta}$).

FIG. 16.—Observed values of F_1-ionization (dotted curves 2 and 1, y proportional to $\cos \zeta$ and $\sqrt{\cos \zeta}$, respectively).

FIG. 17.—Dots and crosses, observed y of E for normal day and during eclipse at Washington and Sydney, Nova Scotia, respectively (full line and dotted curves, y proportional to $\sqrt{f} \cos \zeta$ at the two places, respectively).

(5) THE IONOSPHERE DURING A SOLAR ECLIPSE

The total solar eclipse of August 31, 1932, which occurred in Canada and the northern part of the United States, offered an opportunity to observe changes in the ionosphere during the eclipse. A program of measurements was carried out at a number of stations, observations being made during several days before and after the eclipse so that any variations during the eclipse could be clearly determined [1017, 1459, 1503].

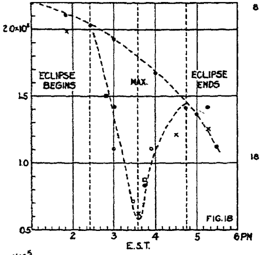


FIG. 18

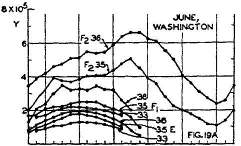


FIG. 19A

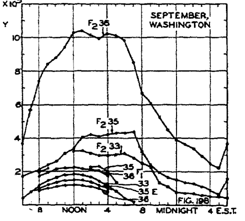


FIG. 19B

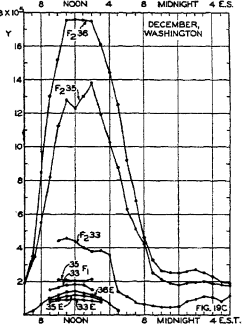


FIG. 19C

FIG. 18.—Dots, observed y of F_1 for normal day and during eclipse at Washington (curves, y proportional to $\sqrt{f}\cos\zeta$ at Washington); crosses, circles, and squares, observed y of F_1 at Sydney, Canada, Newfoundland, and Boston, during the eclipse.

FIGS. 19-A,-B,-C.—Monthly average values of y at Washington (*after National Bureau of Standards*).

Certain stations were chosen for investigating the question [1438], raised by Chapman, whether some of the ionization might be due to particles from the Sun in addition to ultraviolet light. On the supposition that the particles moved in straight lines with a velocity of 1,600 km sec^{-1} the particle eclipse was calculated to occur [1438] north of the Gulf of Maine about two hours earlier than the optical eclipse. Washington and Sydney, Nova Scotia, were well situated for the purpose, each being in the penumbra where the sunlight was reduced to one-tenth at the eclipse maximum, one to the south and one to the north of the path of optical totality; Sydney was in, and Washington outside, the path of the hypothetical particle eclipse.

The results for the E- and F_1-regions are given in Figures 17 and 18. y of E decreased as the Moon's shadow was entered, reaching a minimum value almost exactly—at not more than five minutes after the maximum of the optical eclipse. Similarly for F_1, as seen in Figure 18, except that the radio measurements were not so numerous as in the case of E and the time of minimum ionization was not so accurately determined; it occurred not later than 30 minutes after the maximum of the optical eclipse. The Sydney and other Canadian data gave no evidence of a particle eclipse.

The F_2-layer exhibited no observable deviations from its normal trend during the period of the August 31 eclipse.

A partial eclipse of the Sun occurred on February 3, 1935, at Washington with the maximum at 11^h25^m EST, 30 per cent of the solar disk being covered by the Moon. Ionospheric observations [1052] at Washington showed that, at eclipse maximum, y of E and F_1 was reduced to 0.86 and 0.88, respectively, of its normal values. y of F_2 decreased to a minimum of about 0.58 of its normal average value within nine minutes after eclipse maximum. The opinion was expressed [1052] that, although the dip in y of F_2 seemed directly associated with the eclipse, the low value, 0.58, might not be entirely due to the eclipse because y of F_2 is normally subject to erratic variation. It was concluded that the changes in y of F_2 were different during an eclipse in winter and in summer.

(6) THE IONOSPHERE AND THE SUNSPOT-CYCLE

The data of Figures 4 to 18 were obtained during 1933–34, an epoch of sunspot-minimum and few magnetic disturbances. Therefore they refer fairly well to a period of solar quiescence. The changes in the ionosphere [980, 981, 1470, 1488] during the following years through 1936 are shown in Figures 19-*A*, -*B*, and -*C* and 20. This was a period of increasing sunspots and magnetic activity, the maximum of which should be reached around 1939. It is seen that E and F_1 have evidenced a relatively regular increase during these years and that F_2 in the winter has undergone an increase of more than threefold.

It has been brought out [980, 981] that on the average if the F_2- ionization is high at one hour of the day, it is proportionately high at all hours. Thus, the average monthly noon values of y for F_2 may be taken to indicate the average trend of F_2-ionization at any station. The values for Washington, Huancayo, Watheroo, and Tromsö are plotted in Figure 20 from 1933–37. The arrows on the Hunacayo curve mean that y was greater than the points of the curve by an undetermined amount, f_p being beyond the range of the ionospheric equipment. It is seen that the maximum-in-height F_2 ionization-density over the Earth has roughly doubled in the past four years. The small dip in the Washington curve (Fig. 18*d*) between November and February may be a real characteristic of the F_2 seasonal variation, for it has been repeated for a number of years. On the other hand, the monthly average virtual heights of all the regions have showed no marked change with increasing sunspots, being in 1937 about the same as they were in 1933. In general, at any station the F_2 virtual height was high when y was low, and vice versa. This relation was true for individual days as well as for weekly or monthly averages. The foregoing facts are for average conditions; detailed ionospheric variations during magnetic storms, as far as they are known, are described in Section VIII.

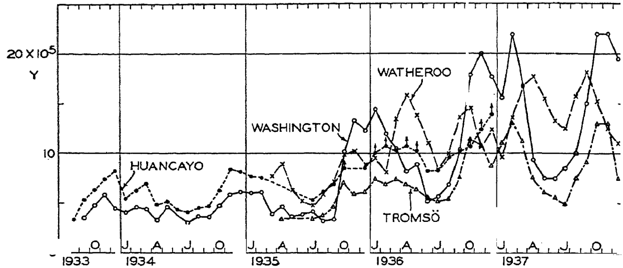


FIG. 20.—Monthly average noon values of y (*after Carnegie Institution of Washington and National Bureau of Standards*).

III. THE THEORY OF THE IONOSPHERE

(1) IONIZATION BY THE ULTRAVIOLET LIGHT OF THE SUN

The more important agencies which may conceivably produce the ionization of the upper atmosphere are the ultraviolet light, α, β, and neutral particles from the Sun, stellar radiations, cosmic rays, meteors, cosmic dust, thunder-clouds, and ionizing radiations from terrestrial sources. The last mentioned may be ruled out immediately because the ionization of the lower atmospheric strata increases rapidly with the height for the first few km. Cosmic rays produce only about 1.4 ions $\mathrm{cm}^{-3}\ \mathrm{sec}^{-1}$ at sea-level and their ionization at higher levels is negligible [1462, 1468], unless there exist components of considerable intensity and much softer than any yet observed. Meteors have been observed to produce short-lived increases in E-ionization [1511]. Ionospheric effects of lightning and thunder-clouds have been looked for without definite success. Effects of stellar radiations, of cosmic dust, and of the ions of space swept up by the Earth are as yet undemonstrated. Hypotheses of α, β, and neutral particles from the Sun are tentative, and it may be said that no phenomena have been discovered which point unmistakably to the existence of such particles.

There remains the ultraviolet light of the Sun as deserving first consideration; it is the only hypothesis of those just mentioned which may be put in even partly quantitative terms. The ionizing effects of its action have been examined [1041] and, as described in the following paragraphs, fair agreement is found with the ionospheric observations.

Let i_λ be the intensity of sunlight of wave-length, λ, at a height z cm above sea-level. If the direction of the light makes an angle, ζ, with the vertical, then

$$di_\lambda = \beta_\lambda n i_\lambda dz/\cos\zeta \tag{12}$$

where β_λ is the molecular (or atomic) light absorption-coefficient of the atmosphere for light of wave-length λ. (12) is the usual definition of β_λ. Putting (1) into (12) and integrating gives

$$i_\lambda = E_\lambda \cdot \exp\,(-\beta_\lambda n/p\cos\zeta) \tag{12a}$$

where E_λ is the intensity of light of wave-length λ for $z = \infty$, that is, outside the atmosphere.

Let $q_\lambda d\lambda$ be the number of ion-pairs (electrons and positive ions) produced cm^{-3} sec^{-1} by the light in the wave-length region λ to $(\lambda + d\lambda)$ and let W be the energy of ionization of the molecule or atom. Then

$$q_\lambda d\lambda = (\beta_\lambda n E_\lambda d\lambda/W) \cdot \exp\,(-\beta_\lambda n/p\cos\zeta) \tag{13}$$

on the assumption that all of the absorbed energy causes ionization. The total electron-production will be $\int q_\lambda d\lambda$, the integral to be taken over all regions of the spectrum which cause ionization. There will be a similar integral for each type of molecule or atom in the atmosphere and a more complete expression for the electron-production would be represented by the sum of such integrals. However, too little is known about the photoelectric ionization of gases to permit a complete expression to be dealt with, and therefore we simplify (13) by dropping the subscript λ and write

$$q = (\beta n E/W) \cdot \exp\,(-\beta n/p\cos\zeta) \tag{14}$$

where q denotes the number of ion-pairs, or electrons, produced cm^{-3} sec^{-1} at a height, z. If the light is totally absorbed, or nearly so, in passing down to a height, z, the total number of electrons, $\bar{q}$, produced sec^{-1} in a one-cm^2 column which extends from outside the atmosphere to z is

$$\bar{q} = \int_z^\infty q\,dz = E\cos\zeta/W \tag{15}$$

From (14) the maximum value of q with respect to z is

$$q = pE \cos \zeta / W\epsilon \tag{15a}$$

and is therefore proportional to cos ζ. To show how q varies with z and ζ the (q,z)-curves are plotted in Figure 21 for various values of ζ with β arbitrarily chosen so that the curves lie in the levels around 200 km.

On a simple photoelectric theory of ionization, Bohr's Theory, the light which causes ionization is in that region of the spectrum extending to shorter wave-lengths from the limit λ_0, or frequency ν_0, of the principal series. It is assumed that the spectral-energy curve of solar radiation is that of a black body at a temperature, $t_1 = 6000°\text{K}$. The total energy cm^{-2} radiated in the frequency-range from ∞ to ν is

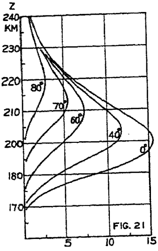


FIG. 21

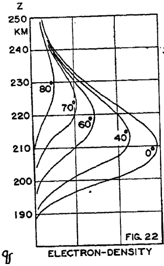


FIG. 22

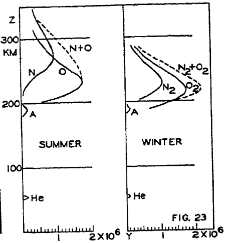


FIG. 23

FIG. 21.—Values of q calculated from equation (14).
FIG. 22.—(y, z)-curves from equation (18a).
FIG. 23.—Theoretical (y, z)-curves.

$$\int_\infty^\nu (8\pi h\nu^3/c^2)(e^{-a\nu} - 1)d\nu \tag{15b}$$

where $a = h/kt_1$. Integrating (15b) yields approximately

$$(8\pi h/c^2)(\nu^3/a + 3\nu^2/a^2 + 6\nu/a^3 + 6/a^4)e^{a\nu} \tag{15c}$$

For ν in the ultraviolet the first term only of (15c) may be retained without causing an error greater than 15 per cent. Then the solar energy, E erg cm^{-2} sec^{-1}, falling vertically on the top of the atmosphere is

$$E = f(8\pi\nu^3 kt_1/c^2)e^{-h\nu/kt_1} \tag{16}$$

where $f = 1/184{,}000$ is the fraction of the total sphere subtended at the Earth by the Sun. Values of E for wave-length regions of the far ultraviolet portion of the spectrum are given in Table 5, column 2. Taking the longest wave-length of the spectral regions of column 1 to be λ_0, the ionization-potentials, V, calculated from the relation

$$Ve = h\nu_0 = hc/\lambda_0 = W$$

are given in electron-volts in column 3. In column 4 are the values of $E/W = \bar{q}$, the number of ion-electron pairs produced $\text{cm}^{-2}\ \text{sec}^{-1}$. It is seen that for the smaller ionization-energies $\bar{q}$ is quite large. Naturally such calculations, which depend on the extrapolation of solar black-body conditions into the far ultraviolet, are at best only approximations, and perhaps very distant ones, for line-emission and absorption undoubtedly play a predominating rôle in the solar ultraviolet spectral-energy distribution.

TABLE 5.—*Ionization produced by various spectral regions of solar energy*

Wave-length, Ångstroms	E, ergs	V, volts	E/W, ion-pairs
1,250–1,000	4	10.0	2.5×10^{11}
1,000–900	9×10^{-1}	12.3	4.6×10^{10}
900–800	8×10^{-3}	13.7	3.8×10^{8}
800–500	5×10^{-4}	15.2	1.8×10^{5}
500–0	1×10^{-11}	24.5	0.3

The absorption-coefficient for light in the continuum below the series limit usually employed is that deduced by Kramers [1474] from classical electromagnetic theory assuming a special law of electron-capture. Kramers' theory gives, neglecting terms of unit-order,

$$\beta = \frac{16\pi^2}{3\sqrt{3}} \frac{Z^2 e^6 c^5}{h} \frac{h\nu_0}{(h\nu)^3} \tag{17}$$

where Z is the nuclear charge, or atomic number. β has values only for $\nu \geqq \nu_0$, or $\lambda \leqq \lambda_0$. From quantum theory Gaunt [1449] derived a slightly different expression. There appear to be no direct experimental tests of (17) in the optical range; the formula can scarcely claim an accuracy better than an order of magnitude. Rosseland [1505] has commented, "One sometimes has the feeling that the applicability of this formula has been strained beyond the breaking point." For *He*, *A*, *N*, and *O* the first ionization-potential, W, is 24.46, 15.69, 14.48, and 13.55 volts [1428], λ_0 is 503, 786, 850, and 910 Ångstroms, and at λ_0 from (17) β is 4.75×10^{-18}, 9.46×10^{-16}, 1.69×10^{-16}, and 2.52×10^{-16}, respectively.

(2) THEORETICAL IONIZATION-CURVES

In order to determine the ionization resulting from the photoelectric action of solar radiation the law of recombination of electrons and ions must be known. Three recombination-formulas are described below. Two, derived from theory, deal with recombination of electrons and positive ions with and without the emission of radiation; and one, based on experiment, deals with the attachment of electrons to neutral oxygen molecules. In the following paragraphs the ionization-curves are first worked out for a static atmosphere, that is, an atmosphere in which there are no diffusion of the ionization, no mass motions, no winds, and no changes in the ionizing source. Actually, diffusion does occur, there may be winds and mass motions, and the source does change, for the Earth turns under the Sun. The modifications of the static curves occasioned by these effects are then discussed.

Recombination involves interaction of some sort between electrons and ions. The simplest type of interaction is collision and the number of collisions $\mathrm{cm}^{-3}\ \mathrm{sec}^{-1}$ is proportional to y^2. If a fraction of the collisions results in recombination we may define α such that

$$\alpha y^2 \tag{17a}$$

is the rate of recombination and α is the recombination-coefficient.

In a static atmosphere photoelectric equilibrium is established when the rate of production equals the rate of loss of the ionization at all points, and therefore

$$q = \alpha y^2 \tag{18}$$

With (14) this gives

$$y^2 = n(\beta/\alpha)(E/W) \cdot \exp\,(-\beta n/p \cos \zeta) \tag{18a}$$

Illustrative (y,z)-curves from (18*a*) are plotted in Figure 22 with β chosen so the curves are in the region of 200 km. Similar curves at 100 km are much the same.

From (18*a*) y is a maximum at a height, z, where

$$n = (p/\beta) \cos \zeta \tag{18b}$$

and the value at the maximum is

$$y = \sqrt{(p/\alpha)(E/W\epsilon) \cos \zeta} \tag{19}$$

which may be written

$$y = y_0\sqrt{\cos \zeta} \tag{19a}$$

Now the daytime and seasonal values of y of E and of F_1 conform closely with (19*a*), as shown in Figures 4, 5, 6, and 16. Therefore a detailed theory of recombination or loss of ionization must yield (19), or something equivalent, in order to agree with the ionospheric observations.

Recombination with the emission of radiation is essentially the Saha [1446, 1481, 1508] Theory of the ionization of a gas in photoelectric, thermodynamic equilibrium with radiation. The reaction-isobar of a gas at temperature, t_1, ionized by and in equilibrium with black-body radiation of a temperature, t_1, is

$$x^2P/(1 - x^2) = (2\pi m h^{-2})^{\frac{3}{2}}(kt_1)^{\frac{5}{2}}e^{-h\nu_0/kt_1} \tag{20}$$

where x is the fraction of atoms ionized and P is the total pressure. For a gas at temperature, t, and radiation at a temperature, t_1, Pannekoek [1496] showed that the right-hand side of (20) must be multiplied by $t^{\frac{3}{2}}/2t_1^{\frac{3}{2}}$. Then, it being noted that $P = nkt$ and $x = y/n \ll 1$, (20) becomes

$$y^2 = n2^{\frac{1}{2}}(\pi mkh^{-2})^{\frac{3}{2}}t_1t^{\frac{1}{2}}e^{-h\nu_0/kt_1} \equiv An \tag{20a}$$

which is of the same form as (18a).

The recombination-coefficient, α, may be derived in a general way from the definitions of i and β, namely, that i is the intensity of the ionizing light and β the atomic absorption-coefficient for that light. Then the rate of electron ion-pair production $q = \beta nE/h\nu_0$. For equilibrium $q = \alpha y^2$, or

$$y^2 = \beta nE/\alpha h\nu_0 \tag{20b}$$

Identifying (20a) and (20b) gives

$$\alpha = \beta i/Ah\nu_0 \tag{20c}$$

Substituting in (20c) the values of β from (17), of E from (15c) using only the first term, and of A from (20a) leads to

$$\alpha = 32\pi(2\pi m/27k)^{\frac{1}{2}}(Z^2e^6c^3/m^2)(\nu_0^3/h\nu^3t^{\frac{1}{2}}) \tag{20d}$$

If some formula for β is used other than (17), a value of α different from (20d) will result. Since α has been derived directly from β, it contains the errors and uncertainties of β. Setting $\nu_0 = \nu$ and introducing numerical values yields an average value of α in the continuum near to and ending with ν_0,

$$\alpha = 1.02 \times 10^{-11}Z^2/t^{\frac{1}{2}} \tag{20e}$$

For $t = 360$°K, α is 3.4×10^{-11}, and 2.6×10^{-11} for O and N, respectively.

Mohler [1485] has recently determined α to be 2×10^{-10} for mercury-vapor at pressures below 10^{-1} mm and an electron-temperature about 2000°K, and 3×10^{-10} for cesium-vapor at pressures below 10^{-2} mm and temperature 1200°K. The corresponding values from (20e) are 1.5×10^{-9} and 8.9×10^{-11}. The agreement is perhaps as good as could be expected in view of the fact that (20e) contains no correction owing to screening of the nuclear charge, Z, or additional terms to include effects of line-absorption at frequencies below ν_0.

We may now determine the (y,z)-curves of the gases of the atmosphere by means of (18a) with E, β, and α given by (16), (17), and (20e), respectively. Consider the case of a summer day and a winter day. In the mid-hours of a summer day in temperate and tropical latitudes when the Sun is above 45°, that is, $\zeta < 45°$, assume that nitrogen and oxygen molecules above 200 km are dissociated to atoms. For atomic nitrogen, distributed according to Table 4, y reaches a maximum value, 9.5×10^5, from (19), at a height, $z = 272$ km. The (y,z)-curve for $\zeta = 0$ is drawn in Figure 23. Similarly for atomic oxygen y reaches a maximum value, 2.0×10^6 at $Z = 228$ km. However, since wave-lengths below 850 Ångstroms are absorbed by nitrogen leaving only the region from 850 to 910 Ångstroms to ionize oxygen, y must be reduced to 1.8×10^6. On this basis the (y,z)-curve is drawn in Figure 23.

Similar computations for argon and helium yield (y,z)-curves at 174 and 55 km with maximum values of y, respectively, 1.8×10^5 and 860. The curves are in Figure 23, those for helium being enlarged. However, there is some question whether these regions of ionization exist in theory; for if the variation of β with ν given by (17) is anywhere near correct, the ultraviolet frequencies necessary to produce the regions are almost totally extinguished by supernatant oxygen and nitrogen.

Therefore, the total ionization is the summation of the O- and N-curves, obtained approximately by taking the square root of the sum of the squares of the abscissas. This gives the $(O + N)$-curve with a maximum, $y = 1.8 \times 10^6$, at about 240 km, which is somewhat above the summer noon values for F_2, at Washington, Watheroo, and Huancayo of 0.5, 0.6, and 0.9×10^6 in 1934, 1935, and 1937, respectively. Qualitative agreement between the observed and theoretical values of y may be secured by the assumption of heating of the F_2-atmosphere under the Sun. This will give rise to an expansion of the atmosphere and a reduction of y. Winds will blow away in all directions from the sub-solar point and may cause a complicated world-wide distribution of F_2-ionization.

For the Sun below 45°, that is, $\zeta > 45°$, as in the morning and afternoon hours in all latitudes and in midday hours in winter temperate latitudes, it is assumed that nitrogen and oxygen are in the molecular state at all heights, being distributed as in Table 3. The (y,z)-curves for N_2 and O_2 are given in Figure 23 for $\zeta = 60°$. When combined they amount to a single bank of ionization, shown by the $(N_2 + O_2)$-curve, at about 215 km with $y = 1.8 \times 10^6$. The height is in accord with the apparent height of the unbifurcated day F-region; y is in agreement with the observed Washington winter noon values for F_2 which have increased from 0.5×10^6 in 1934 to 2×10^6 in 1937.

Thus the view of the theory is that when sunlight passes down into the atmosphere, light in the continuum of long-wave limit, 910 Ångstroms, is absorbed by oxygen and nitrogen and forms F_2. The theory provides no explanation of F_1- or E-region. If the equations are true, no light in the continuum above ν_0 can reach E-levels in effective amount. It seems probable, however, that frequencies below ν_0 may penetrate to 100-km levels and give rise to F_1- and E-ionization. No quantitative investigation has yet been made on this point.

Several theories of radiationless recombination of electrons and positive ions have been proposed. Probably the theory of J. J. Thomson [1296, 1297, 1448, 1517] has yielded the best agreement with the results of experiments at room temperature and pressures ranging from several atmospheres to 10^{-4} atmosphere. The essential idea of the theory was that an electron, or negative ion, upon collision with a positive ion would combine with the ion only if the energy of recombination were dissipated in some way, as by the action of a neutral particle. Therefore, recombination required a sort of three-body collision, the energy of recombination going into heat. The theory took no cognizance of the possibility of recombination by a two-body collision with the emission of radiation. This is in contrast with the Saha-Pannekoek theory (20*d*), which considered only two-body collisions and neglected the three-body case. Loeb [1477] mentioned that at very low pressures the Thomson theory may degenerate to a two-body radiationless collision-case.

For pressures below 10^{-2} atmosphere Thomson showed that the rate of recombination of ion-pairs cm^{-3} was αy^2 where

$$\alpha = 2\pi(u^2 + u'^2)^{\frac{1}{2}}(2e^2/3kt)^3(1/y + 1/y') \tag{21}$$

u and u' are the velocities of thermal agitation of negative and positive particles, respectively, and γ and γ' their free-paths among the molecules of the gas. For $t = 360°\text{K}$, (21) reduces to

$$\alpha = \gamma n \tag{21a}$$

where γ is 1.1×10^{-23} for electrons and positive ions and 1.7×10^{-25} for negative and positive ions. Upon comparing α of (20*e*) and (21*a*) it is seen that they are equal for n of order 10^{12}, which from Table 3 occurs at about $z = 150$ km. Therefore, above 150 km, α of (20*e*) is the greater and controls the ionization-equilibrium, and below 150 km α of (21*a*) is the greater and controls the ionization.

According to experiment in the laboratory free electrons become attached to oxygen molecules to form relatively stable negative ions; they do not become attached appreciably to the other particles of the high atmosphere. The rate of attachment is

$$by \tag{21b}$$

The attachment is usually stated in terms of h, the probability of electron-capture at a collision. Then

$$b = uh/\gamma \tag{22}$$

where u is the temperature velocity of the electron and γ the free-path among the oxygen molecules. From Bradbury's [1434] measurements h increased rapidly with the decrease of electron-energy for energies below one electron-volt. At 0.2 electron-volt, the lowest energy at which observations were made, corresponding to a temperature of 770°K, h was 2.5×10^{-4}. This in (21b) with $t = 360$°K gives $b = 2 \times 10^{-12}n'$, where n' is the density of oxygen molecules.

Now (21b) with $b = 2 \times 10^{-12}n$ gives a loss of electrons much more rapid than that due to the recombination of (20d) or (21) and therefore would be expected to control the ionization-equilibrium. However, for F_1- and F_2- regions, (21b) gives very low values of y, a very rapid decrease of y at night, and leads to $y = y_0 \cos \zeta$ instead of to (19). These results conflict with observation and force the conclusion that (16) does not hold in the F-region, either because all the oxygen there is atomic, or the ions are unstable, or because for some unknown reason the laboratory value is not applicable to the conditions at great heights. As discussed later, similar difficulties with (22) in the E-region are not so acute.

In considering the diffusion of the ions and electrons we assume that each element of volume of the upper atmosphere is approximately electrically neutral and remains so at all times. It is true that in the lower atmosphere there is a gradient of electric potential and a vertical electric current, but it seems probable that these effects do not extend to altitudes above, say 40 km. The charged particles which are produced by the ultraviolet light in equal positive and negative amounts throughout each element of volume diffuse about to attain if possible their equilibrium-pressures. The diffusion of the electrons is governed by the motions of the positive ions, for because of electrostatic forces electrons do not stray away unless accompanied by equal numbers of positive ions, and, conversely, wherever the positive ions go equal numbers of electrons flock along with them.

Let N denote the number of electrons, or ion-pairs, which move upward by diffusion across a cm² each sec. It has been shown [1041] that

$$N = -0.41\,\gamma u(py + dy/dz) \tag{23}$$

where p is given by (1a) and the free-path, γ, by (2a). The velocity of thermal agitation $u = 10^5$, and (23) becomes

$$N = -10^{-19}(py + dy/dz)/n \tag{24}$$

The manner in which diffusion modifies the various static (y,z)-curves is calculated by approximate methods. We take as an example from Figure 22 the static (y,z)-curve for $\zeta = 0$ for atomic nitrogen with maximum $y = 9.5 \times 10^5$ at 280 km. All the constants of the curve are known and from these the total rate of production of electrons in a 1-cm² column from 280 km outward to space is 5×10^7. The rate of diffusion of electrons cm^{-2} downward across the 280-km level is, from (24), 2.3×10^9, which is two orders of magnitude greater than the production. Therefore the ionization diffuses downward until a new (y,z)-curve is formed for which the production is balanced by diffusion and recombination. This occurs at about 230 km. In the new family of curves the relation, $y = y_0\sqrt{\cos \zeta}$, still holds approximately. Since diffusion varies inversely with the molecular density, n, as shown by (24), it decreases rapidly at the lower levels. A static (y,z)-curve with maximum at 200 km is lowered by diffusion to about 180 km and for one at 140 km and below the effect of diffusion is negligible.

The ionization which has been discussed is that of photoelectric equilibrium, as if the Earth did not move with respect to the Sun. Actually, in spite of the fact that the Earth turns under the Sun and equilibrium can never be rigorously attained, the ionization does approach equilibrium with solar radiation fairly closely during the daylight hours not too near dawn and sunset. To show this, let the rates of production and loss of electrons at any place in the atmosphere be Q and L, respectively. The time rate of change of y is

$$(dy/dt) = (Q - L) \tag{25}$$

We assume for simplicity that $\zeta = \omega t$, where ω is the angular velocity of the Earth on its axis. From (15a) $Q = q \cos \omega t$ at the maximum of the (y,z)-curve, q being the value of Q when $\zeta = t = 0$, and for the recombination of (18) $L = -\alpha y^2$. Then (25) becomes

$$(dy/dt) = q \cos \omega t - \alpha y^2 \tag{26}$$

Similarly, for the attachment of (21b)

$$(dy/dt) = q \cos \omega t - bn'y \tag{27}$$

(27) has been solved explicitly [1041] and (26) approximately [999, 1041] From each equation y increases to a maximum after noon, the time of the maximum being nearer to noon the smaller a or bn' is. It is observed that the daily maximum of y of E and F_1 occurs within an hour of noon, any displacement after noon, if it exists, being concealed by the errors due to the erratic phenomena under observation. Therefore the rates of production and loss of ionization are rapid compared with the changes due to the relative motions of the Earth and Sun, and the equilibrium-equations (19a) and (22) are satisfactory approximations of the more exact relations (26) and (27) from about 8 A.M. to 4 P.M.

At night (26) becomes

$$(dy/dt) = -\alpha y^2 \tag{28}$$

The solution of (28) is

$$y = 1/(1/y_0 + \alpha t) \tag{29}$$

where t is measured from sunset and y_0 is the value of y at sunset.

(3) THEORY OF THE *E*-REGION

From Figures 4, 5, and 6 it is seen that y of E at Washington during the year beginning May, 1934, is represented within ten per cent by (19a) with $y_0 = 1.45 \times 10^5$, or

$$y = 1.45 \times 10^5\sqrt{\cos \zeta} \qquad (30)$$

Furthermore the eclipse data, as shown in Figure 17, agreed well with

$$y = 1.45 \times 10^5\sqrt{f \cos \zeta} \qquad (31)$$

where f is the fraction of the solar disk uncovered by the Moon. Therefore the E-ionization during the day is in accord with the hypothesis of ion-production by solar ultraviolet light and recombination of the two-body collision-type of (17a).

The Huancayo data of Figure 7 were also in accord with (19a) as shown by the comparison of the observed points with the dotted curve.

Since the full-line curves of Figure 22 show that z for maximum y increases with ζ, the height of E would be expected to vary with season, latitude, and hour of day, being 10 to 20 km higher at 8 A.M. and at 4 P.M. than at noon and 10 to 20 km higher in temperate latitudes than at the equator. The observed changes in the virtual height of E, mentioned in an earlier section and shown in part in Figures 8 and 9, are in keeping with these theoretical inferences. Although in general the true heights of a region are never the same as the virtual heights, in the case of E the difference is not great, and the agreement between theory and observation appears to be genuine.

The high value of the attachment of electrons to oxygen molecules gives support to the view that in the E-region a twofold reaction occurs, namely, the ionizing radiation first produces positive ions and free electrons and the free electrons become rapidly attached to form negative oxygen ions. If the ratio of the rate of electron-attachment to the rate of ionic recombination were sufficiently great, ionization of the E-region would be predominantly ionic, rather than electronic, and so far as the refraction of radio waves is concerned, the disappearance of ions would be by the recombination-formula (21a), and y of E would agree with (19) and hence with observation. Numerically, however, the ratio of b/α should be about three times greater than the value given by (21a) and (22). This would occur either if α of (21a) were a little less, or if Bradbury's [1434] curve of h against electron-energy continued to increase with decreasing energy in the domain below 0.2 electron-volt. Further experimental knowledge of attachment- and recombination-coefficients might contribute to the question in an important manner.

Regarding the sudden and erratic increases observed in E-ionization there is no explanation at the present time. Whether the changes are occasioned by winds which release or concentrate the solar energy stored in the high atmosphere, or by some other agency, cannot be said.

(4) THEORY OF THE F_1-REGION

The values of y of F_1 are in fair accord with (19*a*) and yield $y_0 = 2.5 \times 10^5$, or

$$y = 2.5 \times 10^5\sqrt{\cos \zeta} \tag{32}$$

although the agreement is not quite so good as for E. In Figure 15, which refers to monthly average noon values at Washington, the dotted curve given by (32) bears away a little from the observed points, the deviations probably being within the error of experiment. The Huancayo F_1-curve of Figure 10 gives $y = 2.4 \times 10^5$, which agrees well with (32). In Figure 16, y from (19*a*) is plotted for various months in curves 1, the curve for each month being passed through the observed noon value. This was done to bring out the extent to which (19*a*) fitted the daily variation, apart from the seasonal variation; it is seen to fit well. (32), modified to $y = 2.5 \times 10^5\sqrt{f \cos \zeta}$, agreed with the eclipse observations as shown in Figure 18. At the same time, y from the electron-attachment relation (22) is plotted in the dotted curves 2 of Figure 16 and in Figure 15 for the purpose of showing that (22) does not agree with the observations so satisfactorily as does (17*a*). On the whole it appears that the F_1-data are fairly well accounted for by the ultraviolet-light hypothesis with recombination according to (17*a*).

In the case of the seasonal variation of noon values of y of F_1 it is possible that the slight discrepancy between the observed points and the dotted curve, $\sqrt{\cos \zeta}$, of Figure 15 may be real and that future data may show that what now is regarded as agreement within experimental error is a genuine, although not large, discrepancy. It is also probable that the F_1-region is merely a lower boundary or protuberance of the F_2-region which lies above. In such case a complete theory of the F_1-region must envisage possible complicating effects of the F_2-region.

The virtual heights of F_1 at both Washington and Huancayo, shown in Figures 8 and 9, decrease somewhat during the morning to a minimum in the midday hours and rise again in the afternoon, being 10 to 30 km lower at noon than at about 8 o'clock and 4 o'clock. The average noon virtual height over the year at Washington is about 30 km above that at Huancayo. The (y,z)-curves of Figure 22 for a static atmosphere agree approximately with the observed changes in F_1-height, for they indicate a height at noon from 10 to 30 km below the heights at 8 o'clock and 4 o'clock, and an increase in average height at noon of about ten km from the 40° latitude. However, in the case of F_1, diffusion of the ionization would be expected to modify the static (y,z)-curves in such a way as to render the height of maximum y nearly constant through the day and at various latitudes, provided there are no other changes in the high atmosphere below F_1 with latitude and hour of the day. Furthermore, the virtual heights of F_1 are probably from 10 to 40 km greater than the true heights, and changes in them may not be the same as changes in the true heights. Therefore no great stress can be laid on the agreement between the static theory and the virtual-height observations.

(5) THEORY OF THE F_2-REGION

In an earlier Section and Figure 23 it has been shown that the photoelectric action of solar ultraviolet radiation is adequate to produce an ionization at F_2-levels of the observed order of magnitude. To this extent the theory was satisfactory. We may pursue the matter a little further by considering the night-time degradation of F-ionization. The data of Figures 10 to 14 and 19-A, -B, and -C show that y of F decreased by roughly a factor of 5 from 6 o'clock to 2 o'clock. If the decrease is due to recombination unaffected by other factors, a questionable assumption, we may take $y = 5 \times 10^5$ at 6 o'clock and find from (29) that $\alpha = 3 \times 10^{-10}$. This is nearly ten times the theoretical value from (20d). About all that can be done is to remark that astrophysical theory is satisfactory as to orders of magnitude but is none too successful when pushed to higher precision.

Now an ultraviolet-light theory of a static atmosphere yields a single maximum in the daily variation of y, which is contrary to the double maximum observed in tropical latitudes. An additional hypothesis is necessary. This is secured by the assumption of the daytime expansion [1043] of the F_2-atmosphere due to heating and dissociation of the molecules as outlined in Section I and Table 4. In the absence of the vertical expansion the F_2-ionization would center about a 250-km level and would increase to a maximum in the early afternoon. The expansion spreads the ionization through the levels from 250 km to 350 km and hence reduces the ionization-density, y. During a day in which ζ does not become less than 40° even at noon, the vertical expansion is slight and y reaches a maximum shortly after noon. This is in accord with the observed values of z and y for F_2 during a winter day at Washington, as shown in Figures 9 and 13. During a day in which ζ approaches 0° at noon, y begins to increase in the morning owing to the increasing light-intensity. Soon, in spite of the fact that the total number of electrons in a vertical column of the atmosphere through F_2 continues to increase, the expansion is rapid enough to make y decrease. Hence, y passes through a maximum during the morning. In the afternoon the march of events is reversed; the total ionization decreases with the lowering Sun, but the contraction of the atmosphere is sufficiently rapid to effect an increase in

y for a time. Therefore y passes through another maximum in the afternoon. These conclusions are in accord with the observed variations in y during the day at Washington and Watheroo in summer and at Huancayo the year round. The morning maximum in summer is usually less pronounced at Washington and Watheroo than at Huancayo. Additional evidence in favor of the theory is found in the curves of Figure 20 for Washington and Watheroo which are in latitudes 39° north and 30° south, respectively. According to the theory the curves should cross at equinox, with winter values at Washington above the summer values at Watheroo and summer values at Washington below the winter values at Watheroo. The curves of Figure 20 show this trend. They also show other variations which are not yet completely explained [1041].

There is another important effect [1043]. Owing to the expansion of the F_2-atmosphere, winds in levels about 250 km blow away in all directions from the region directly beneath the Sun. Westward from the subsolar point, and hence in the morning hemisphere, the stream of F_2-air moves against the rotation of the Earth, is checked, and becomes turbulent as the whitecapping waves in a tide-rip, whereas eastward, and hence in the afternoon hemisphere, the stream moves with the rotation of the Earth and remains smooth and undisturbed. The eastward breeze may even displace the afternoon maximum of y an hour or so toward evening. The effects are in accord with the observations of F_2 which at the equator record a greatly disturbed and erratic layer in the morning and a less disturbed ionization in the afternoon with a broad maximum at 6 or 8 o'clock.

All in all, the two hypotheses, ionization by solar ultraviolet light and expansion of and winds in the F_2-atmosphere due to heating and dissociation by sunlight, appear to be able to account for the main features of F-ionization. The expansion notion may also account for the night variation of F in winter temperate latitudes, for the high atmosphere may be assumed to contract slowly as the night progresses until sufficient concentration of the ionization takes place to cause y to increase for a time. This would account for the curious recrudescence of F-ionization observed in the small hours of a winter morning at Washington. Such an explanation may be correct but seems to require stretching the theory pretty far.

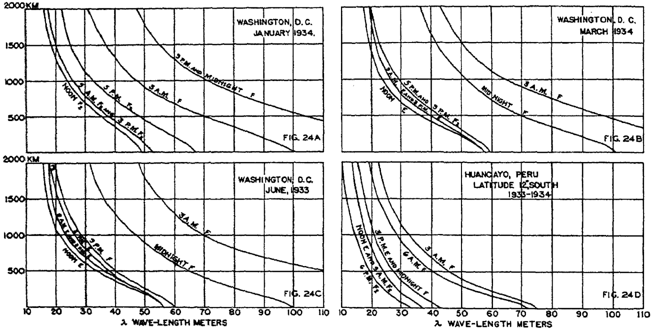
Further, there is an uncertainty in the case of F_2 and F_1 which may or may not turn out to be important. Because of diffusion it is difficult to see how a stable bank of ionization can exist much above 250 km. For example, if the ionization is produced in levels above 300 km, the downward diffusion of the ionization is so rapid that the equilibrium-position of the maximum of the region is at 250 km; and yet F_2 appears to be considerably above 250 km. Theoretically, if the virtual heights are known for a wide range of frequencies, it is possible to calculate the actual (y,z)-curve. When this was done for a particular case [1487], the real heights were found to be more than 100 km below the virtual heights. Thus the virtual heights may give an impression of the location of F_2 more false than has been suspected.

IV. SKIP-DISTANCES OF RADIO WAVES

The skip-distance, $2s$, of a radio wave of wave-length, λ, is related to y and z by the relation [1104]

$$\frac{ye^2\lambda^2}{\pi m} = 1 - \frac{\sin^2 s/r}{\sin^2 s/r + (1 + z/r - \cos s/r)^2} \tag{33}$$

where r is the radius of the Earth, and e and m are the charge and mass



FIGS. 24-*A*,-*B*,-*C*,-*D*.—Skip-distances.

of the electron; CGS EMU are used. The skip-distance varies with the state of polarization of the radio wave and with the direction of propagation with respect to the magnetic field of the Earth. The amount of the variation is not large, being in most cases less than 15 per cent of $2s$, and (33), which refers to the polarization or propagation such that the electric vector of the wave is parallel to the magnetic field of the Earth, is a fair average among the possible variations. Equation (33) is approximate in that it is based on the assumption that the waves experience reflection from the ionized region, as if the region were a mirror. The approximation has been shown [1104] to be valid in certain cases, although the waves probably are bent back to the Earth by refraction in the region. In applying (33) to the case of several ionized regions, the assumption is made that the density of ionization between the regions is small; the assumption probably leads to no serious error.

The values of the skip-distances were calculated by means of (33) with the values of y and z of Figures 8 to 14 and are plotted in the curves of Figures 24 for various times of day and seasons of the year 1933–34. The period was one of minimum solar activity and it is of interest to compare the calculated skip-distances with the average daytime temperate-zone skip-distances observed [1104] in 1923, also a period of minimum solar activity. The comparison is shown in Table 6; it is seen that the averages in the last three columns, which are the calculated values taken from Figures 21, 22, and 23, agree well with the observed values in the second column.

TABLE 6.—*Average day skip-distances*

λ, meters	Observed 1923–24, km	From Fig. 24-*A*, January, 1934, km	From Fig. 24-*B* March, 1934, km	From Fig. 24-*C* June, 1933, km
40	400	400	500	400
30	700	800	800	700
20	1,200	1,500	1,600	1,400
16	2,000	2,300	2,200	2,200

The curves of Figures 24-*A*, -*B*, -*C*, and -*D* offer a more complete world-wide survey of the skip-distances than has heretofore been available. Figure 24-*A* shows that the winter skip-distances reach their greatest lengths around midnight and then become shorter from 2 to 4 o'clock. It is not certain that this effect has been observed. The effect is probably erratic, for the recrudescence of ionization in the small hours of winter night to which the effect is due is erratic. It is a matter of general experience that the skip-distances in the early morning hours are variable and ill-defined.

In Figures 24-*A*, -*B*, -*C*, and -*D* no skip-distance curves are given for the sunrise period between 3 o'clock and 9 o'clock, because the ionospheric data for all regions are not sufficiently complete during these hours. The data indicate roughly that the average skip-distances do not change much between 3 o'clock and sunrise and that after sunrise they shorten rapidly.

It is hardly necessary to remark that in the case of the longer waves, for which the skip-distances are less than 200 or 300 km, the ground-wave may often fill in the skipped region. The skip-distance is essentially the range within which the sky-wave cannot be refracted to the Earth.

Since there are several regions of ionization, the skip-distances for each epoch were calculated for each region by the use of y and z for the region. The region which gave the shortest values of $2s$ was of course the region which controlled the skip-distances for the epoch in question. In the curves of Figures 24-*A*, -*B*, -*C*, and -*D* the region which controlled the skip-distances is marked on each curve. From this certain new facts stand out. For example, it is seen from Figure 24-*C* that at Washington in summer the skip-distances during the day are controlled by the *E*-region. This means that low-angle rays, which are those of long-distance propagation, are turned down by *E* and do not get through to F_1 or F_2 at all. Whereas in winter (Fig. 24-*A*) the skip-distances are controlled by F_2, and hence low-angle rays pierce through *E* and F_1 to be refracted by F_2. Therefore long-distance short-wave communication in winter is by rays which experience less than half the number of earth and ionospheric reflections which they experience in summer, since F_2 is more than twice as high as *E*. Further, absorption of energy from the radio wave is greater in *E* than in F_2, since the molecular density in *E* is greater than in F_2. Thus we find an explanation of the well-known fact that in general long-distance short-wave communication is better in winter than in summer.

The summer-afternoon case, as shown by the 5 o'clock curve of June at Washington (Fig. 24-*C*), presented the complexity that for waves from about 20 to 40 meters the skip-distances were controlled by *E* and for waves below 20 meters the skip-distances were controlled by F_2. One might conclude that better temperate-zone summer-afternoon short-wave communication would be achieved by decreasing the wave-length until penetration of *E* was secured. However, such a conclusion is hardly safe in view of the fact that the values of y of Figures 11 to 14 are monthly average curves of ionization which fluctuated within fairly wide limits from day to day; and any conclusion, as the foregoing, which demands high accuracy of the ionization-curves, is not dependable.

Other possibilities appear from the ionization-curves. For example, a ray of waves of the correct wave-length and correct angle to the horizontal to pass through *E* transmitted southward from Washington might be refracted downward by F_1 or F_2 to *E* again over, say Florida, and because of the increased y of *E*, due to the lower latitude, the ray might not penetrate *E* but be refracted upward again to F_1 or F_2; and so on, until the ray finally reached the latitude where it could get through *E* down to Earth again. Such a ray would have an abnormally long skip. It is similar for east-west propagation, where the change in y of the regions of ionization with longitude at any specified instant of time might introduce various complicated effects.

The skip-distance curves of Figures 24-*A*, -*B*, -*C*, and -*D* rise rapidly with decreasing wave-length and soon become imaginary. The value of λ at this point, denoted by λ_1, is the shortest wave-length useful for long-distance communication, since waves shorter than λ_1 are not refracted back to the Earth again. λ_1 may be determined from the $(2s,\lambda)$-curves of Figure 24 or, what amounts to the same thing, may be calculated directly from the relation [986]

$$ye^2\lambda_1/\pi m = 1 - [r/(r+z)]^2 \tag{34}$$

where λ_1 refers to the region of height, z, and ionization-density, y.

The values of λ_1 are tabulated in Table 7. They are open to some uncertainty, as much as 20 per cent, for (34), being a limiting case of (33), depends on the same assumptions as (33) but is more sensitive to errors in the assumptions. Table 7 agrees in general with the observed values as far as they are known. A possible discrepancy is that, according to the Table, λ_1 for noon at Washington is slightly greater in June than in January, whereas qualitative experience appears to indicate the reverse.

TABLE 7.—*Values of* λ_1

Time	Washington, 1933–34, meters			Huancayo, 1933–34, yearly average, meters
	January	March	June	
6 A.M.	..	..	..	18
9 A.M.	15	19	17	13
Noon	14	17	16	13
3 P.M.	15	19	17	13
5 P.M.	19	17	16	10
9 P.M.	42	17	17	12
Midnight	42	32	28	13
3 A.M.	28	38	42	20

The skip-distances, $2s$, of Figures 24-*A*, -*B*, -*C*, and -*D* and the shortest useful wave-lengths, λ_1, of Table 7 refer to 1933 and 1934, a period of approximately sunspot-minimum. The average day skip-distances of 1927 and 1928, a time of sunspot-maximum, were about 200, 700, 1,400, and 2,200 km for wave-lengths 40, 30, 20, and 16 meters, respectively [1516]. Comparing these with Table 6 it is seen that $2s$ decreased by about 40 per cent from minimum to maximum sunspots. Since September, 1937, the National Bureau of Standards has published each month ("Proc. Inst. Rad. Eng.") the average monthly ionospheric data for Washington and an analysis of radio wave-propagation conditions derived from the data.

V. ELECTRODYNAMICS OF THE UPPER ATMOSPHERE

(1) IONIZATION OF THE UPPER ATMOSPHERE

For the purpose of the following Chapters the results of the ionospheric observations, described in Section II, may be restated in very brief form. The observations show that for the Sun overhead the equivalent electron-density, y, for E, F_1- and F_2-regions is about 1.5×10^5, 3×10^5, and 10×10^5 at about 100, 200, and 300 km, respectively, but yield no complete information about the ionization below, between, and above these levels except that the values at the levels are not exceeded. These facts are illustrated in the dotted curve of Figure 25. On the assumption, as yet unchallenged, that the upper atmosphere is electrically neutral, or approximately so, y is also the density of positive ions.

Two scales of abscissas are marked in Figure 25, the lower scale in terms of electron-density and the upper scale in terms of ion-density, the mass of the average atmospheric ion being assumed to be 3.6×10^{-23} gram. The observed magnetic splitting of the radio echoes returned from the ionosphere indicates that above 200 km, that is, for F_1 and F_2, the ionization is largely electronic. Hence in Figure 25 for the part of the dotted curve above 200 km the lower scale applies. Experiment has not yet determined definitely whether E-region is mainly electronic or ionic; at present a majority of experiments indicates ions and a few experiments indicate electrons. Therefore, for the curve below 200 km either of the abscissa-scales may be used, or a scale representing a suitable mixture of ions and electrons. As brought out later, the matter is of vital importance to the theories of magnetic variations, for if future experiment proves that the ionization below 200 km is predominantly electronic all the theories will fall to the ground or require fundamental modification.

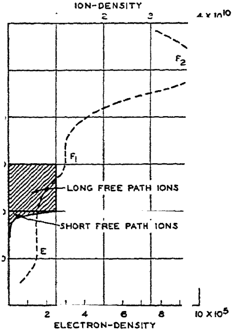


FIG. 25.—Dotted curve, ionosphere at equatorial noon, 1933–34, sketched from observation; shaded area, ion-banks assumed in terrestrial magnetic theory.

It was shown in Figure 6 that the observed values of y, the maximum point on the (y,z)-curve, for E during 1933–34 conformed to the relation, derived from the hypothesis that the ionization is caused by the ultra-violet light of the Sun,

$$y = y_0 \sqrt{\cos \zeta} \tag{35}$$

where ζ is the zenith-angle of the Sun and y_0 is the value of y for the Sun overhead, that is, $\zeta = 0$. (35) is valid for from 0° to about 85°. For F_1 and F_2 the observed values of y departed considerably from (35), but a reasonable theory was proposed [1043] which accounted for the departures. Thus there is at present no objection to the hypothesis that the ionization over the day hemisphere is expressed approximately by (35). The average ionization during the night is about one-tenth of the noon value.

(2) LONG AND SHORT FREE-PATH REGIONS

Two regions of the high atmosphere are differentiated [1041], the short free-path region and the long free-path region. In the first region the radius, r, of magnetic gyration of the ions or electrons is large compared with the mean free-path, γ; in the second r is small with respect to γ. r is given by

$$r = mu/He \tag{36}$$

where u, m, and e are the velocity of temperature-agitation, mass, and charge, respectively, of the charged particle and H is the component of the Earth's magnetic field perpendicular to u. The free-path, γ, is, respectively, for ions and electrons

$$\gamma = 1/\sqrt{2}\pi na^2 \qquad \text{and} \qquad \gamma = 4/\pi na^2 \tag{37}$$

where n is the molecular density and $a = 3 \times 10^{-8}$ cm is the kinetic-theory diameter of the average atmospheric molecule or atom.

γ for ions from (37) is given in the last column of Table 8; the first two columns of the table are taken directly from Table 3. From (36) r is 20 and 1.3 cm for ions and electrons, respectively, for $H = 0.3$ gauss as at the equator. The ratio, γ/r, in the case of ions becomes large above 150 km; for electrons it is large above 100 km. Therefore at the equator the short free-path region merges into the long free-path region at about 150 km for ions and 100 km for electrons. In temperate latitudes $H = 0.5$ gauss, and for a temperature of 360°K, the respective levels are about ten km higher. If oxygen and nitrogen of the high atmosphere are in the atomic state, n is greater than the values of Table 1 and the foregoing levels are 10 to 30 km higher.

TABLE 8.—*Theoretical molecular density n and free-path γ in the high atmosphere*

z, km	n	γ, cm
60	9.9×10^{15}	0.03
80	1.0×10^{15}	0.25
100	1.6×10^{14}	1.5
120	2.6×10^{13}	9.6
140	4.4×10^{12}	57
160	7.7×10^{11}	320
180	1.4×10^{11}	1,800
200	2.5×10^{10}	10^4
250	2.5×10^{8}	10^6
300	7.7×10^{6}	10^7
350	7.3×10^{5}	10^8
400	4.1×10^{5}	10^9

(3) CONDUCTIVITY

The conductivity, σ, per unit-volume of an ionized gas is in EMU, in the absence of a magnetic field,

$$\sigma = \Sigma y^2 e^2 \gamma/2mu \tag{38}$$

where y is the density of charged particles; the summation is taken over all classes of charged particles. In a magnetized ionized gas the conductivity along H is undisturbed by the magnetic field and is given by (38). The conductivity, σ', across the field is approximately [1077]

$$\sigma' = \sigma/(1 + \gamma^2/r^2) \tag{39}$$

A more rigorous calculation by Page [1494] gave

$$\sigma' = \sigma(1 + 2\,\gamma^2/r^2)/(1 + \gamma^2/r^2) \tag{40}$$

Equation (39) was derived by averaging the effect of collisions in shortening the free magnetic spiraling of the ions and (40) by the same averaging process and taking into account motion of the ions in the direction of the impressed field. They differ but slightly and both yield $\sigma' = 0$ and σ in the long and short free-path regions, respectively.

(4) MOTION OF IONS IN CROSSED FIELDS, GRAVITATIONAL MAGNETIC DRIFT

Let an ion of charge, e, and mass, m, in a magnetic field, H, be acted on by a constant force, X. X and H are along the positive directions of the X and Z axes, respectively. The equations of motion of the ion are

$$\left.\begin{aligned} m\ddot{x} &= X + He\dot{y} \\ m\ddot{y} &= -He\dot{x} \\ m\ddot{z} &= 0 \end{aligned}\right\} \tag{41}$$

Let $\omega = -He/m$ and for $t = 0$, $\dot{x} = x_0$, $\dot{y} = \dot{y}_0$, $\dot{z} = z_0$. The solution of (41) yields

$$\left.\begin{aligned} \dot{x} &= \dot{x}_0 \cos \omega t + (\dot{y}_0 + X/He) \sin \omega t \\ \dot{y} &= -X/He + (\dot{y}_0 + X/He) \cos \omega t - \dot{x}_0 \sin \omega t \\ \dot{z} &= \dot{z}_0 \end{aligned}\right\} \tag{42}$$

From (42) the ions move in cycloidal paths with a drift in a direction perpendicular to X and H. If the mean values of $\dot{x}_0$, $\dot{y}_0$, $\dot{z}_0$ are zero, the average of $\dot{x}$, $\dot{y}$, $\dot{z}$ with respect to time is, since the periodic terms vanish,

$$0,\ -X/He,\ 0 \tag{43}$$

Therefore the ions drift [286, 824, 1493] along Y with a constant velocity X/He. The averaging eliminates correctly the kinks in the cycloidal paths of the ions.

At the equator, where H is horizontal and north, the ions are pulled downward by gravity and from (43) drift in a horizontal direction with a velocity, v, given by

$$v = mg/He \tag{44}$$

The positive ions move eastward and the negative particles westward, constituting an eastward electric current termed "gravitational magnetic drift current." At 200 km altitude at the equator $g = 920$ cm sec^{-2}, $H = 0.29$ gauss, and v is 11.8, 5.3, and 1.3 cm sec^{-1} for nitrogen molecules and oxygen and helium atoms, respectively.

From (43) an electric field, E, normal to H causes ions of both signs to move perpendicularly to E and H with the same velocity

$$v = -E/H \tag{45}$$

For E eastward, ions at the equator drift upward, and downward for a westward E. The drift is not an electric current since ions of both signs move in the same direction with the same velocity.

The gravitational magnetic drift (44) and the electric magnetic drift (45) are fully effective only in the long free-path region and are zero in the short free-path region. It may be shown after the manner of Pederson [1077] that they vary with the free-path approximately according to the ratio

$$1/(1 + r^2/\gamma^2) \tag{45a}$$

(5) DYNAMO-EFFECT

The dynamo-effect is the electromotive force, E, induced in a conductor moving with velocity, v, across a magnetic field, H, given by

$$E = -vH \tag{46}$$

where E, v, and H are the components along the positive directions of the X, Y, and Z axes, respectively. This is Faraday's Law of electromagnetic induction. The short free-path ionized region of the upper atmosphere is a conductor and if, owing to winds, thermal expansion, or tidal forces, it moves across H, electromotive forces according to (46) are developed. If conducting paths exist, the electromotive forces give rise to currents, and these in turn to magnetic effects.

Motions of the long free-path regions across H also develop E in accord with (46), since the force which sets the region in motion causes, by (43), a drift of positive and negative charges equivalent to the movement of charges required to yield E of (46).

(6) DIAMAGNETISM

The long free-path region of the upper atmosphere is diamagnetic [1024]. The intensity of magnetization, i, of free charges, as ions and electrons, of density, y, is

$$i = -ykt/H \tag{47}$$

where t is the temperature Kelvin and $k = 1.372 \times 10^{-16}$ erg deg^{-1}. Just as in the case of the drift-currents i varies with the free-path according to (45a), being zero in the short free-path region.

VI. SOLAR DIURNAL VARIATION OF TERRESTRIAL MAGNETISM

(1) INTRODUCTION

The magnetic field of the Earth is observed to undergo slow and rapid changes, the former measured in years and the latter in days, hours, or minutes. The magnitudes of the magnetic variations are always small from a world-wide point of view, for they rarely amount to more than a few per cent of the total magnetic field of the Earth. Gaussian harmonic analysis has shown that the slow variations are due to changes of some sort in the crust or the interior of the Earth and that the more rapid changes arise from influences in part external to the surface of the Earth. The influences are not in the low atmosphere and therefore, if on the Earth at all, must be in the high atmosphere.

The rapid changes are of two types, periodic and erratic. The periodic types, associated with solar and lunar days, are known as the solar and lunar diurnal variations of the terrestrial magnetic field. The erratic types, known as magnetic disturbances or storms, are thought to be associated mainly with such solar activities as sunspots, faculae, and eruptions; certain of the erratic types may possibly be due to extra-solar causes, as meteors and the sweep-up of material by the Earth in its travel through space.

The following pages present a summary of the more important facts of magnetic variations and the several theories which have been advanced in explanation. Since aurora and magnetic disturbance are in general closely connected, a discussion is given of the facts and theories of the aurora. By the same token the allied subjects of the light of the night sky and the solar corona should also be treated; this, however, is not done, as space in this volume forbids.

All theories of terrestrial magnetic variations assume in common that the variations arise from the effects of electrical charges and differ in their choice of effect and the situation of the charges. Three effects are recognized, dynamo-action, diamagnetism, and gravitational magnetic drift-currents. The more important theories place the charged particles in the upper atmosphere. Other theories, for the most part inchoate or discarded, place the charged particles at distances of several Earth's radii from the Earth; such particles are not truly in the upper atmosphere.

(2) OBSERVED FACTS OF THE SOLAR DIURNAL VARIATION

The observed daily variation, denoted by S, of the terrestrial magnetic field for various geographic latitudes is given in Figure 26, in which N, V, and W, the components of S in the north horizontal, vertical, and west horizontal directions, respectively, are plotted against local time [22]. For latitudes below 40°, N increases to a maximum during the daylight hours and for latitudes above 40° to a minimum. The day maximum or minimum of N occurs from one to two hours before noon or between 10 and 11 o'clock. The amplitude of S increases with sunspots, being nearly twice as great at sunspot-maximum as at sunspot-minimum; N is about 30γ (γ is 10^{-5} gauss) and 15 γ, respectively, for the two epochs. Harmonic analysis indicates that about three-fourths of S arises from overhead causes and one-fourth from induced currents in the Earth [327].

(3) DYNAMO-THEORY

The dynamo-theory of S, originally proposed by Balfour Stewart, was extended in considerable detail by Schuster [327]. The theory conceived that S was caused by horizontal movements of conducting regions of the high atmosphere across the terrestrial magnetic field. The motion induced electromotive forces according to (46) which gave rise to electrical currents and hence to the magnetic variations of Figure 26. The type of atmospheric current necessary to cause S, worked out by Bartels [23], is shown in Figure 11 of Chapter VII; the numbers along the lines of current-flow are in 10^3 amp. Thus the Figure indicates in the Northern Hemisphere in the day a current-sheet of 62,000 amp wheeling counterclockwise around a center at about 40° latitude and 11 o'clock, and at night a current-sheet of 32,000 amp wheeling in the opposite

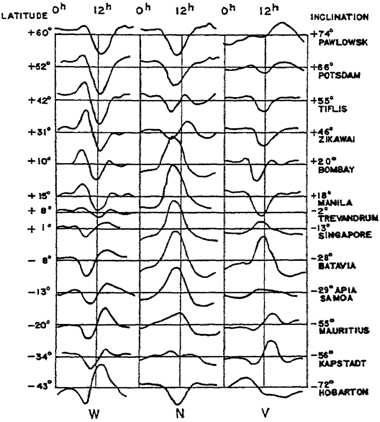


FIG. 26.—Daily variation of terrestrial magnetic elements at equinox—the inclination gives the magnetic latitude (*after Angenheister*).

direction, or an excess of day over night of 94,000 amp. An epoch midway between maximum and minimum sunspots is referred to. The maximum current-density occurs at 11 o'clock at the equator and has the value 3×10^{-5} CGS EMU excess day-over-night value.

The horizontal movements of the high atmosphere were calculated from the observed daily fluctuation of the barometric pressure. Two components of barometric variation are recognized, a regular component of 12-hour period and of amplitude one mm of mercury at the equator and a less regular, erratic component of 24-hour period and amplitude about 0.3 mm. The origin of the two components, whether thermal or tidal, has been much discussed [496]. If the solar semidiurnal component is tidal, some new hypothesis must be brought in, as a 12-hour resonance of the free atmosphere [1437], to account for the fact that it is 15 times larger than the lunar semidiurnal barometric variation, of amplitude 0.063 mm, whereas the tide-raising force of the Sun is only two-fifths that of the Moon. The solar diurnal component may reasonably be supposed to be a thermal effect and to result from a redistribution of the atmosphere caused by winds which blow from expanding regions heated by the Sun.

Qualitatively, winds blowing away in all directions from a high-pressure area at noon at the equator will induce current-sheets of the type of Figure 11 of Chapter VII. For day in north latitudes above 40°, northward velocities across the vertical component of H induce a westward electromotive force which drives the circular current-sheet of that Figure, provided the reasonable assumption is made that the conductivity is a maximum under the Sun and decreases with increasing zenith-angle of the Sun to small values at night. Similarly a 12-hour tidal movement of the atmosphere will induce current-systems of the type of Figure 11 of Chapter VII with components of 12 and 24 hours, the relative amplitudes of the components depending on the relation assumed for the dependence of the high atmospheric conductivity on the zenith-angle of the Sun.

As the result of an extensive mathematical analysis Schuster [327] found that the electric currents inferred from the barometer readings, although of the correct type, disagreed in phase with those of Figure 11 of Chapter VII. In fact they were nearly in opposition, yielding a maximum value of N at 2 to 4 P.M. in contrast to the observed time, 10 to 11 A.M. A discrepancy was brought out between the observed and theoretical ratios of the amplitudes of the 24-hour and 12-hour periodic terms derived from harmonic analysis, the former being about 9 and the latter 3. The conclusion, not altogether unexpected, was drawn that if the dynamo-hypothesis were to be retained at all the wind-systems of the upper reaches of the atmosphere could not be inferred in a simple manner from sea-level barometer readings. Discussion of more recent magnetic and meteorological data by Walker [333], Chapman [186, 282, 284], and others confirmed Schuster's conclusion. The theory was left dangling.

The conductivity, σ, of the high atmosphere was calculated on the uncertain assumption that the 12-hour barometric variation was due to atmospheric tides of a simple nature such that the tidal motion is uniformly distributed through a vertical section of the atmosphere. The one-mm amplitude of the variation may be taken to mean that $\frac{1}{2} \times 760$ of the atmosphere remains fixed with reference to the Sun, and hence that there is a horizontal ebb and flow of the atmosphere with an average velocity of 1/1,520 of the peripheral velocity of rotation of the Earth. At the equator this amounts to an atmospheric tidal current of 30 cm sec^{-1} or one km hr^{-1}.

From (46) we write $\sigma = i/vH$; then, with $i = 3 \times 10^{-5}$, $H = 0.3$ gauss, and $v = 30$, find

$$\sigma = 3 \times 10^{-6} \text{ EMU}$$

for equatorial noon, which is the value obtained by Schuster. However, it must not be supposed that the foregoing brief calculation represents adequately Schuster's more complete treatment; it merely presents correctly the physical ideas and yields a numerical value of the correct order.

If atmospheric resonance is assumed, the air-motions will differ from those which were calculated from purely tidal effects in a non-resonating atmosphere and the foregoing value of σ is meaningless. If the solar barometric variation is attributed to heating of the atmosphere by the Sun, the atmospheric winds and the electrical conductivity required by the dynamo-theory cannot be calculated unless the heating at all heights in the atmosphere is known or assumed.

The dynamo-theory may be examined anew in the light of ionospheric measurements. Of the three daytime ionospheric regions only E contributes to the conductivity across H, for F_1 and F_2 are in the long free-path region. Referring to Figure 25, assume that ionization of E is constant from 100 to 150 km and is composed of equal numbers of electrons and positive ions of density, y, given by (35) with $y_0 = 1.5 \times 10^5$, which is the maximum number of electrons permitted by radio ionospheric measurements interpreted according to (7). The conductivity of E-region may then be calculated over the day hemisphere. The electrons cannot move across H and the conductivity of a one-cm^2 vertical column from 100 to 150 km is, from (35) (38), (39), and Table 8,

$$\sigma = 7.2 \times 10^{-10} \sqrt{\cos \zeta} \tag{48}$$

The average σ, for day latitudes from 0° to 40° is about 5×10^{-10}; this is approximately four orders of magnitude below Schuster's value.

The total eastward current flowing between 0° and 40° latitude is 94,000 amp excess day over night, or an average current-density across of one-cm^2 vertical column of E-region of 2×10^{-5} EMU. To produce the current by dynamo-action requires north-moving winds in day latitudes above 40°, where the average vertical component of H is about 0.5 gauss, of velocity, from (46), $2 \times 10^{-5}/5 \times 10^{-10} \times 0.5 = 8 \times 10^4$ cm sec^{-1} or 2,900 km hr^{-1}. The existence of such high winds appears improbable and we conclude that the dynamo-theory fails under the assumptions which have been made concerning E-ionization.

An acceptable dynamo-theory would require winds of reasonable velocity, say less than 100 km hr^{-1}. Therefore E-conductivity must be at least 30 times greater than 5×10^{-10}. But E-conductivity cannot be increased by assuming more electrons, for the maximum number of electrons permitted by radio ionospheric measurements has already been assumed. A way out is to appeal to the fact that the radio measurements as yet do not exclude the possibility of ions up to the density given by (35) with $y = 6 \times 10^9$. If this density exists from 100 to 150 km, σ is 4×10^{-5} and the breeze necessary to produce the 94,000 amp is only 35 meters hr^{-1}, which is a fairly gentle breeze. Thus, there is some latitude between the limits at present set by E-ionization observations; that is, electrons or ions, and the type of ionization which yields an E-conductivity requisite to a reasonable dynamo-theory. This was clearly recognized in early considerations of the ionosphere [1041] in which an arbitrary selection of electron- and ion-densities of E between the permissible limits was made.

The foregoing conclusion also applies to those portions of all theories of magnetic variation described later which attribute the magnetic effects to electric currents in conducting regions of the high atmosphere; reasonable causes of such currents cannot be proposed so long as the short free-path ionization is predominantly electronic.

Further pursuits of the dynamo-theory entail a scrutiny of secondary effects to see either that they provide desirable explanations of observed facts or that they do not lead to conflict with observation. For example, north-moving air in day latitudes above 40° induces a westward electromotive force which, together with H, by (45), causes the long free-path ionization, F_1 and F_2, over the day hemisphere to drift with a component downward, and over the night hemisphere upward. These drift-velocities are of the same magnitude as the north-moving breeze. Therefore a dynamo-theory which assumes, for example, a 40-km hr^{-1} breeze must be prepared to accept the consequences of a 20- to 40-km hr^{-1} downward drift of day F_1- and F_2-ionization and a similar upward drift of night F-ionization.

We take leave of the dynamo-theory with the remark that the theory has been neither proved nor disproved. To this extent it is a possible theory, but to be reasonably possible E-ionization must be largely ionic.

(4) DIAMAGNETIC THEORY

Gunn [1024] remarked that the ionization in the long free-path region was diamagnetic according to (47) and worked out a diamagnetic theory of S. Over the daylight hemisphere the intensity of magnetization, i, of a one-cm² vertical column of the long free-path region containing y charged particles was assumed to be given by

$$i = i_0 \cos \zeta \tag{49}$$

and at night i was assumed to be less than one-tenth the value at noon. The diamagnetism of such a distribution was shown [1024] to produce a magnetic field in close accord with the observed curves of Figure 26. A repetition of the calculations by Chapman [997] led to the same conclusion.

Introducing (47) into assumption (49) gives

$$y't = y'_0 t_0 \cos \zeta \tag{50}$$

where y'_0 and t_0 refer to $\zeta = 0$.

Ionospheric observations secured after the development of the theory indicate that $y' \sim \sqrt{\cos \zeta}$; they support the view that t increases to a maximum near midday and therefore are in good qualitative agreement with assumption (49).

Quantitative agreement with the observed magnitude of S, that is, a horizontal component of H of external origin of about 15 γ at equinoctial noon at the equator for an epoch midway between minimum and maximum of sunspots, required that y'_0 be 5×10^{16} for temperature at noon of 360°K and, from (47), a less value for a higher temperature. From the dotted curve of Figure 25, on the assumption that the ionization is in terms of pairs of electrons and positive ions as given by the lower scale of abscissas and that y of F_2 is 10×10^5 constant from 300 to 400 km, y'_0 is 3×10^{13} charged particles. This is about 1/1,700 of the 5×10^{16} required by the diamagnetic theory. If, however, the portion of the curve from 150 to 200 km is mainly ions, as given by the upper scale of Figure 25, the 5×10^{16} charged particles can be accounted for.

No clear explanation of the observed minimum of N at about 10 A.M. at the equator (Fig. 26) is offered by the diamagnetic theory; the simple expression (49) of course gives a minimum at noon. It was pointed out [1024] that an increase of the average height of the ionization during the day of 30 km to a maximum at 2 P.M. would advance the phase of the diamagnetic effect into the forenoon hours. Ionospheric height-measurements indicate a maximum height at about noon but do not definitely rule out the possibility of a two-hour shift into the afternoon. This is due not so much to experimental inaccuracy as to the fact that the measurement always yields a virtual or optically equivalent height and not a true height.

In a discussion of diamagnetism Cowling [54, 55] concluded that there exist electric currents at the boundary of a diamagnetic region which cancel the effect of diamagnetism outside the region. The argument was a repetition of an older one by Bohr (thesis) and by Van Leeuwen [1475] in connection with the theory of diamagnetism of metals. In reaching the conclusion Cowling assumed implicitly that the collisions of ions were perfectly elastic. If, however, it is assumed, and there is experimental evidence in support of the assumption [1440], that after collision there is as good a chance of an electron or ion starting out in one direction as in any other, then the peripheral currents disappear and the diamagnetic effects remain [1494]. Thus, Cowling's analysis points out how dependent the phenomena are on the exact mechanism of collision.

Altogether the diamagnetic theory is in about the same position as the dynamo-theory in that it requires a number of charged particles in the high atmosphere larger than the number at first sight indicated by ionospheric measurements—the existence of which is not definitely denied by the measurements. It is simpler than the dynamo-theory since it does not call for a world-wide wind-system in the high atmosphere.

(5) Drift-current theory

A qualitative theory of S was sketched by Chapman [286] based on gravitational magnetic drift-currents of the long free-path ionization. For the more general case in which H and g make an angle, ϕ, with each other, (44) becomes

$$v = mg\,(\sin\phi)/He \tag{51}$$

For a uniformly magnetized sphere, and the Earth approaches this quite closely, H at latitude θ is given by

$$H = H_0(1 + 3\sin^2\theta)^{\frac{1}{2}} \tag{52}$$

where $\cos\theta = 2\tan\phi$ and $H = 0.32$ gauss is the value of H at the equator at sea-level. From (51) and (52)

$$v = (mg/He)[\cos\theta/(1 + 3\sin^2\theta)] \tag{53}$$

from which $v = 0$ at the magnetic poles and $v = 8.5$ cm sec^{-1} at the equator for an average atmospheric ion.

If the total number, y', of ions in a one-cm^2 vertical column of the long free-path region is made up of equal numbers of positive and negative ions of equal mass and charge, the eastward gravitational magnetic drift-current is

$$i = vey' \tag{54}$$

The eastward drift of the positive ions causes an accumulation of positive charge over the afternoon hemisphere; similarly, negative ions drift westward and accumulate over the morning hemisphere. Thus, a westward electromotive force is set up in the long free-path region. The region, however, is electrically connected to the underlying short free-path region for charges can move freely along H to the short free-path region below, particularly in the higher latitudes where H is inclined at a considerable angle to the vertical. Therefore, the westward electromotive force causes currents in the short free-path region, and if there were a suitable world-wide distribution of conductivity in the short free-path region, current-systems similar to those of Figure 11 of Chapter VII would be developed.

Putting the equatorial noon value of $i = 3 \times 10^{-5}$ into (54) gives $y = 2 \times 10^{14}$, which is less than the number required by the diamagnetic theory. The drift-current theory offered no explanation of the forenoon maximum of S. At this point Chapman left the theory with the suggestion that perhaps dynamo-action could somehow be called upon to account for the advance in phase.

The long free-path ionization may contribute to S, through its diamagnetism and its drift-currents. In order that the first be effective the distribution over the Earth must be given approximately by (50); for the second to be effective a similar distribution of long free-path ionization is required and in addition a proper, but unspecified, distribution of short free-path ionization or conductivity. A quantitative investigation [1041] was carried out to determine what the distributions might be; the results were favorable to the diamagnetic theory and unfavorable to the drift-current theory.

In the investigation the following assumptions were made: (1) That the ionization was caused by the ultraviolet light of the Sun; (2) that in the long free-path region directly underneath the Sun $y' = 5 \times 10^{16}$ in accord with the diamagnetic theory, the ionization being, for example, in a bank from 150 to 200 km with $y = 5 \times 10^{9}$; and (3) that at the subsolar point in the short free-path region y was 5×10^{9} at 150 km and decreased approximately exponentially to 1.4×10^{7} at 100 km, which led to $\sigma = 1.44 \times 10^{-5}$. In Figure 25 the shaded portions indicate the nature of the last two assumptions. The shaded area should not extend outside the dotted curve, for that would mean an assumed ionization greater than observed. However, there is no discrepancy, for the dotted curve refers to sunspot-minimum and the shaded area to an epoch halfway between minimum and maximum of sunspots; the ionization is known [1463, 1523] to have increased by roughly 50 per cent from sunspot-minimum in 1923 to maximum in 1928.

From the three assumptions the ionization over the Earth was worked out, ionic recombination, diffusion, and electric and magnetic drift having been taken into account; the details were complicated, and the original papers [1041] should be consulted for them. It came out that the long free-path ionization was in accord with (50) and hence in accord with the diamagnetic theory. The daytime conductivity of the short free-path region was high in tropical latitudes and fell to relatively low values at latitudes above 40°; in the night hemisphere the tropical conductivity was about one-fifth of the day value. Therefore the electrical circuit of the eastward drift-currents of the long free-path ions was completed not by currents sweeping westward in high day latitudes, as Figure 11 of Chapter VII would have it, but partly (three-fourths) by a westward current in the day tropical short free-path region and partly (one-fourth) by an eastward current in the night tropical short free-path region.

In more detail, the world-wide current-system consisted of a flow mainly along the parallels of latitude in the following way: (1) A current-sheet in the daylight hemisphere flowing eastward in the long free-path region which at the sunrise and sunset longitudes divides into two sheets; (2) one of these flows westward on the day side of the Earth in the short free-path underneath (1); and (3) the other sheet continues eastward around on the night side of the Earth. The current is mainly (four-fifths) between the parallels of latitude 40° north and south and falls to lower values at the higher latitudes. The total currents in the three sheets are about 2.1×10^7, 1.6×10^7, and 5×10^6 amp, respectively. The east and west daytime current-sheets subtract from each other, leaving in effect an eastward current of about 5×10^6 amp flowing around the Earth all the time. The distribution of the current with latitude has the shape of curve 2, Figure 27.

From a harmonic analysis of the 1922 survey of the permanent magnetic field of the Earth, Bauer [184] concluded that a portion, about two per cent, is of external origin. His values of the horizontal component, H, of this portion for various latitudes are plotted in curve 1, Figure 27; the scale of abscissas is in γ or 10^{-5} gauss. The calculated horizontal magnetic field of the 5×10^6 amp current flowing around the Earth is given in curve 2, Figure 27. The calculated and observed curves are in fair agreement in tropical latitudes. At high latitudes there is some disparity, but at high latitudes the observed curve is uncertain because the polar data on which it was based were meager. The calculated and observed values of the vertical component of the magnetic field, which are not given here, show an agreement similar to that of the curves of Figure 27.

The conclusion was reached that the gravitational magnetic drift-currents, instead of producing the current-sheets of Figure 11 of Chapter VII, gave rise to a current encircling the Earth of the type to account for the portion of the permanent magnetic field of the Earth of external origin. Analysis [1041] showed that the conclusion did not depend critically on the exact form of the assumed ion-banks in the shaded area of Figure 25.

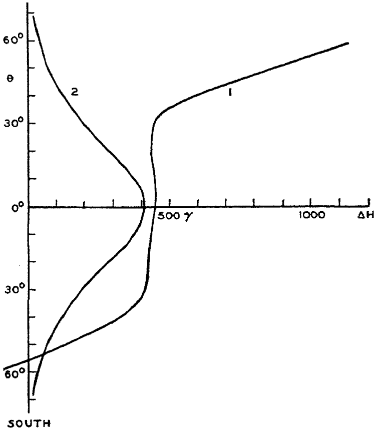


FIG. 27.—Values of ΔH, the horizontal component of the portion of the Earth's permanent magnetic field of external origin, observed (*curve* 1 *after Bauer*) and theoretical (*curve* 2 *after Hulburt*).

VII. LUNAR VARIATION OF TERRESTRIAL MAGNETISM

(1) OBSERVATIONAL DATA

A small variation, L, about 3 γ in amplitude, of the terrestrial magnetic field is recognized as being due to the Moon. The character of L is shown in Figures 28 and 29. In the upper eight curves of Figure 28 the east component of L in the horizontal plane is plotted against lunar hours from observations at Batavia [1431] for various phases of the Moon. It is seen that the variation is much greater during the solar day than at night. An average of the eight curves, given in the lower curve of Figure 28, eliminates the effects of the Sun on L and shows that L is of symmetrical semidiurnal type similar to a tidal variation. In Figure 29 are given the curves of N, V, and W, the north horizontal, vertical, and west horizontal components of L, respectively, for various latitudes averaged from observations at a number of stations [186].

As in the case of S, harmonic analysis indicated that three-fourths, or two-thirds, of L arises from overhead influences and one-fourth, or a third, from induced currents in the Earth. If L is attributed to the magnetic effects of overhead current-systems, the maximum current-density, i, at the equator is about 4×10^{-6} EMU. The amplitude of L was found to vary with lunar distance nearly in the same ratio as the Moon's tide-producing force. In contrast with S, L varies but little with annual mean sunspottedness, although at the same epoch L varies greatly from day to day with the magnetic activity.

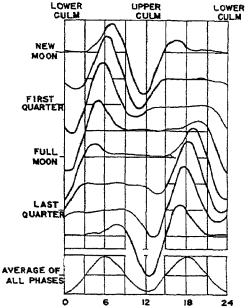


FIG. 28.—Lunar variation in $-W$ at Batavia (*after Bartels*).

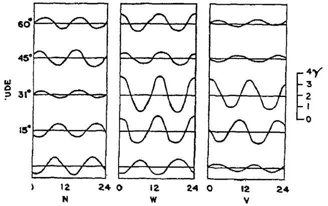


FIG. 29.—Average lunar variation of terrestrial magnetic elements (*after Chapman*).

(2) DYNAMO-THEORY

There is only one theory of L, the Schuster-Stewart dynamo-theory, which was developed in detail, first by van Bemmelen [276] and later by Chapman [186]. The theory ascribed L, just as in the case of S, to the magnetic effects of electrical currents in the high atmosphere. The currents were assumed to be impelled by electromotive forces due to lunar tidal movements of conducting regions of the high atmosphere across the vertical component of the terrestrial magnetic field, the tidal motion being calculated from the lunar barometric variation. Barometric data at Batavia, near the equator, indicated an amplitude of 0.063 mm of mercury for the 12-hour (lunar hour) lunar barometric component; its variation with latitude has not been determined. It was found that the electrical current-systems derived from the calculated atmospheric tidal movements were of the type to account for L. There emerged, however, a phase-difference of 233° between the theoretical and observed values of L, the two being nearly opposite in phase. This was, and is, difficult to explain, for the lunar barometric variation can hardly be other than of tidal origin [1437]. In this respect the L-theory is less open to question than the S-theory which at all times must envisage the complicating possibility of both thermal and tidal effects. The discrepancy in phase of the L-theory was correspondingly more acute than the similar discrepancy in the S-theory.

To determine the high atmospheric conductivity, σ, from L we present, as was done for S, a simple calculation instead of the more complete one [186]. From the lunar barometric amplitude, 0.063 mm, the average velocity, v, of atmospheric tidal ebb and flow is $1/0.063 \times 760$ of the peripheral velocity of the rotation of the Earth. Hence $v = 2$ cm sec^{-1} or 0.07 km hr^{-1}. Putting $i = 4 \times 10^{-6}$, $H = 0.3$ gauss, and $v = 2$ in $\sigma = i/vH$ yields $\sigma = 5 \times 10^{-6}$. This, however, is an average value of σ around the Earth at the equator, since L was derived from an average over a lunar month as indicated in the lower curve of Figure 27. Hence the noon maximum value of σ is greater by a numerical factor 3 to 5, depending on the assumed law of the diurnal variation of σ. Assuming that σ is a function of the cosine of the zenith-angle of the Sun we multiply by 4 to obtain an equatorial noon value and $\sigma = 20 \times 10^{-6}$ EMU.

Approximately the same value was reached by Chapman [186]; it is about seven times the value obtained by Schuster from S. Depending as it does on a theory only partly successful, its correctness is uncertain.

Tentative suggestions were made toward elucidating the departures of the dynamo L- and S-theories from observation, such as atmospheric resonance or viscosity and the possibility that the S- and L-actions occur in different levels of the atmosphere [186]. No set of hypotheses which reconcile the various discrepancies has yet been outlined. Further advance in the theories along the lines followed by previous investigators does not seem immediate, for this would entail statistical extraction of very small quantities from long series of data of many observatories scattered over the Earth.

VIII. MAGNETIC STORMS AND AURORAE

(1) DATA OF MAGNETIC STORMS

The erratic variations or disturbances of the terrestrial magnetic field are so irregular as to defy complete classification. They may occur at any time; they may be world-wide or local. The large disturbances, classed as storms, are almost always world-wide and are usually accompanied by auroral displays. Of the large disturbances those with a sudden commencement are recognized as a definite type. The curves of the continuously registering instruments of the magnetic observatory may have been quiet for some hours, nothing in their appearance suggesting a termination of quiet conditions. Then suddenly a sharp movement begins which in low and middle latitudes is normally the largest in the horizontal component, *H*. In a few minutes *H* may have risen 50 γ or more. A considerable proportion of the largest storms are preceded by these movements and they are not unnaturally regarded as precursors or commencements of the storm. In Figure 30 are given the traces of *H* recorded at Cheltenham Magnetic Observatory, Maryland, for three average world-wide storms which occurred during 1928, illustrating a sudden commencement of the type mentioned in which *H* increased rapidly, a storm which began with a rapid rise and fall of *H*, and a storm which set in gradually. Curves of *H* at a number of observatories [447] are shown in Figure 31 for the short well-defined storm which commenced suddenly at about 7^h GMT, March 14, 1922.

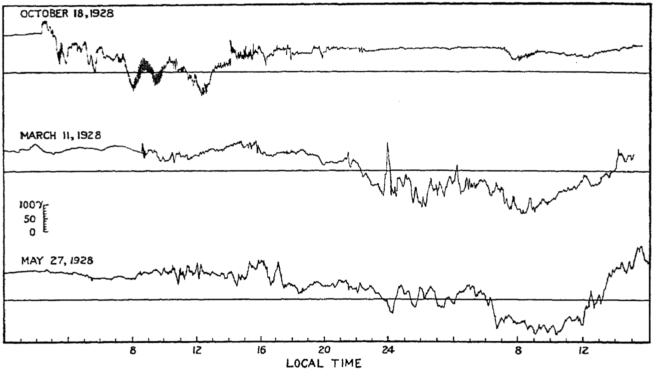


FIG. 30.—Horizontal component of three world-wide storms at Cheltenham Magnetic Observatory, Maryland.

In some cases of world-wide sudden commencements the initial pulse is immediately followed by highly disturbed conditions, in other cases some hours elapse before any further large movement occurs, and in other cases nothing follows during the next 24 hours even remotely resembling a storm. The world-wide sudden commencement appears at all stations simultaneously within three minutes [362, 399, 429, 447]. In Figure 26 of Chapter VII is shown the beginning of the magnetic storm of May 13, 1921, which commenced at 13^h10^m GMT [447]. It was one of the two greatest magnetic storms that occurred between 1908–28. It continued for five days and during that time there were four impulses of the sudden-commencement type, each one of which was simultaneous over the entire Earth.

Aside from sudden commencements of magnetic storms there are almost no prominent features that persist completely around the Earth. An outstanding peak, or a sharp depression, found on a magnetogram almost invariably fades out before it gets halfway around [447]. In examining the magnetograms of 12 years, 1913–24, Wallis [447] found one short sharp disturbance that could be definitely traced entirely around the Earth. This was the sharp wedge-shaped depression in the curves of Figure 26 of Chapter VII near 15^h15^m GMT.

In the records from tropical [43] and middle latitudes any kink in the curve of the characteristic appearance of the sudden commencement is almost always world-wide. This is not true for records from higher latitudes. For example, at Eskdalemuir, Scotland, a considerable number of sudden movements may be found in an average year in addition to the world-wide ones which are not represented at distant stations [72]. At polar stations the record is so agitated during disturbance-periods that almost any feature sought for can be found.

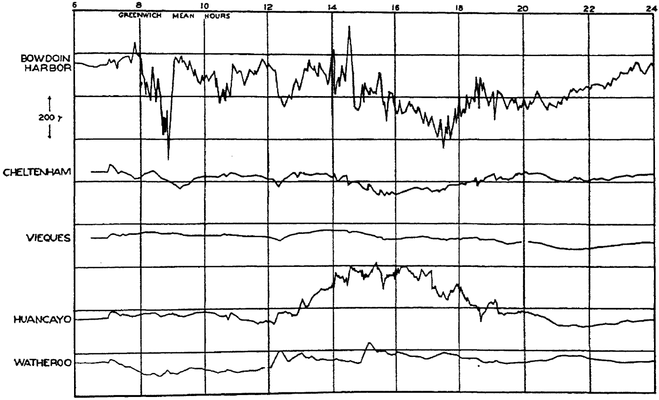


FIG. 31.—Horizontal component at different stations for the magnetic storm of March 14, 1922 (*after Wallis*).

The initial enhancement of H in the sudden commencement is often referred to as the first phase or the impetus [360] of the storm. Sooner or later this is often, but not always, followed by a marked depression of H, referred to as the second phase, in which though generally interrupted by irregularities and oscillations H falls well below the pre-storm value, descending perhaps 100γ in several hours. Finally a recovery-period ensues which in turn may be interrupted by oscillations. Some of these facts are illustrated by the curves of Figures 30 and 31. Chapman [377, 382, 386] selected about 40 storm-curves of this type from a number of observatories, averaged them, and separated them into two features, those features regarded as world-wide and hence measured in "storm-time," or hours from the beginning of the storm, and those features characteristic of the local time of the observatory or the diurnal storm-variations. The average curves [377, 382, 386] are given in Figures 32 and 33. It is seen from Figure 32 that the world-wide storm-variations are about the same at high and low latitudes, and from Figure 33 that the diurnal storm-variations increase in intensity with latitude.

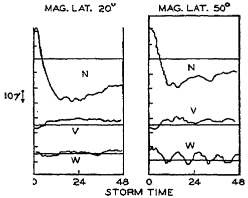


FIG. 32.—World-wide storm-variations at various latitudes (*after Chapman*).

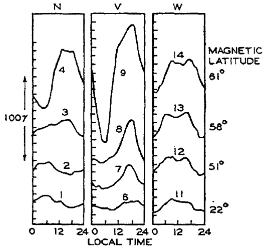


FIG. 33.—Diurnal storm-variations at various latitudes (*after Chapman*).

The energy-density, E, of a medium of permeability, μ, in a magnetic field, H, is

$$E = \mu H^2/8\pi \tag{55}$$

Let x_0, y_0, z_0, and x, y, z be the mean undisturbed and disturbed components of H, respectively, along rectangular axes, and $\Delta x = x_0 - x$, $\Delta y = y_0 - y$, $\Delta z = z_0 - z$. Then the change in E during disturbance is, for $\mu = 1$,

$$\Delta E = (x_0\Delta x + y_0\Delta y + z_0\Delta z)/8\pi + (\Delta\bar{x}^2 + \Delta\bar{y}^2 + \Delta\bar{z}^2)/8\pi \tag{56}$$

or to a close approximation, the second term being neglected,

$$\Delta E = H_0\Delta H/4\pi \tag{57}$$

Wallis [447] calculated the average ΔE for the storms of March 14, 1922, and January 29, 1924, of duration 18 and 26 hours, respectively, using data from the magnetic observatories of Bowdoin Harbor, Sodankylä, Sitka, Cheltenham, Tucson, Vieques, Honolulu, Antipolo, Huancayo, Pilar, Vassouras, and Watheroo. The results, plotted in Figure 34, show that ΔE passes through a broad minor maximum near the magnetic equator, a shallow minimum between magnetic latitudes 20° and 40°, rises to a high maximum between magnetic latitudes 60° and 80°, and descends less steeply toward the magnetic poles, the disturbance-energy at the poles being about the same as at 60°. The march of the ΔE-curve agreed with the curve of average auroral frequency [801, 812]. Identical conclusions were reached by Stagg [442] in a similar investigation.

From Figure 34 the average energy-density of the magnetic storm-field is about 10^{-5} erg cm^{-3}. Multiplying this by the volume of the Earth gives 10^{22} ergs as the total energy of the storm, which may be increased to about 3×10^{22} to account for the storm-field in space. If this energy were received from the Sun in 28 hours, the rate of reception is 3×10^{17} ergs sec^{-1} which is only a small fraction of the 2×10^{24} ergs of sunlight intercepted by the Earth each second.

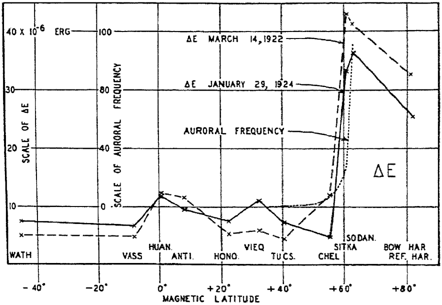


FIG. 34.—Mean values of energy-density, ΔE, of magnetic storms of March 14, 1922, and January 29, 1924 (*after Wallis*).

(2) MAGNETIC DISTURBANCE, RADIO, IONOSPHERE, AND SUN

With the establishment of long-distance communication on short radio waves 15 to 40 meters in length, it was early observed that the circuits were disturbed and often rendered inoperative during strong magnetic disturbance. Analysis [420] showed that the perturbation was essentially a daylight effect as follows: Daylight circuits were disturbed at the commencement of the storm, the full night circuits remaining normal until dawn when they were, or might be, disturbed; the disturbance in the daytime circuits often persisted after nightfall.

Detailed knowledge of the ionosphere during magnetic disturbance is not yet available but may be expected soon, for the program of world-wide ionospheric investigation is being expanded rapidly with continuous recording equipment of increased power and range of radio spectrum. Preliminary conclusions [1473] are

> . . . that the ionosphere disturbances associated with magnetic storms occur principally in the night F- and daytime F_2-layers, and to a lesser degree in the daytime F_1-layer. No such disturbances have been observed in the E-layer. The principal effects are a marked increase in virtual heights, decrease of ionization-densities and increased diffusion of the night F- and daytime F_2-layers, an increased separation of the F_1- and F_2-layers and a sharpening of the F_1 critical frequency. This indicates an expansion and diffusion of the F- and F_2-layers such as might be produced by heating. The ionization of the daytime F_1-layer is also decreased. These effects are regularly observed during the night of and the day following a severe magnetic disturbance recorded at the Cheltenham Observatory. Another effect which has been observed is an increase of ionization-density of the F_2-layer during the beginning of or preceding the magnetic storm.
>
> . . . From April 24 to May 5, 1937, there was a series of very severe magnetic storms, during which the phenomena described above occurred to a greater degree than heretofore observed. During some of these days the ionization-densities [maximum-with-height, (19)] of the night F- and daytime F_2-layers were reduced to as little as 25 per cent of normal, the virtual heights doubled and the layers were highly diffused. The ionization-density of the F_1-layer was reduced to about 75 per cent of normal with no marked change of virtual height.

A discovery was made by Dellinger [1004] when he called attention to a new phenomenon of short-wave radio transmission which occurred on the illuminated half of the globe. It was a sudden disappearance of radio signals for a short time, the complete process of fading out and reappearing lasting usually from a few minutes to an hour; it was simultaneous on all full daylight circuits and was absent from nocturnal circuits. Concomitantly with the radio fade-out there were observed terrestrial and earth-current perturbations, ionospheric changes, and in a number of instances $H\alpha$ eruptions on the surface of the Sun. The magnetic perturbations were of a special type, hitherto unrecognized as such [416, 1012], and were similar to the normal diurnal magnetic variation, S, as though this were suddenly accentuated. The ionospheric disturbance consisted of a sudden cessation of echoes from the ionosphere. When the echoes returned, they showed that the E-, F_1-, and F_2-regions were practically unchanged [979] from their condition previous to occultation. Therefore the effect was attributed to a sudden abnormal increase of ionization in, or slightly below, E which by absorption blotted out the radio echoes and short-wave radio transmission.

Not all solar $H\alpha$ eruptions, which are observed by means of the spectrohelioscope, were accompanied by radio fade-outs, and not all fade-outs were known to be accompanied by $H\alpha$ eruptions, partly because no spectroheliograms happened to be made at the time of the fade-out. However, in a number of instances a close correspondence was observed. For example, on April 8, 1936, an exceptionally brilliant solar eruption was observed at Mt. Wilson [1087] and at Huancayo, Peru [1109], which began at $16^h 45^m$ GMT, increased in brightness until $16^h 47^m$ and returned to normal at about $17^h 03^m$. A striking and wide-spread fade-out of daylight high-frequency radio circuits began at $16^h\ 46^m$ GMT, April 8, lasting from 15 to 30 minutes for various radio frequencies. A magnetic disturbance commenced suddenly at $16^h\ 46^m$; at Huancayo *H* increased 108γ from $16^h\ 46^m$ to $16^h\ 51^m$. Radio echoes from the ionosphere at Huancayo suddenly ceased at $16^h\ 45^m$ and returned again to normal in a little over an hour. The bright hydrogen eruption, the radio fade-out, and the sudden change in *H* and the ionosphere were all phenomena of an unusual and definite character. Richardson [1087] concluded that in this case at least there was strong evidence that the solar activity was directly connected with the terrestrial phenomena and that the energy was transmitted with the velocity of light.

(3) Data of Aurorae

Probably the most complete summaries of the facts of the aurora are those of Chree [806] and of Vegard [848]. There is a zone of maximum auroral frequency [801, 812] about 23° from each magnetic pole as shown in Figure 35 in which the average number of auroral displays in a year is plotted in curve 1 against magnetic latitude. At latitudes above the 67° maximum, curve 1 is dotted for no data are given, merely the statement that in high latitudes aurorae are less frequent. Diffuse auroral clouds and pulsations are observed at heights from about 85 to 150 km and rays and streamers from about 110 to 600 km [807, 835, 845, 851].

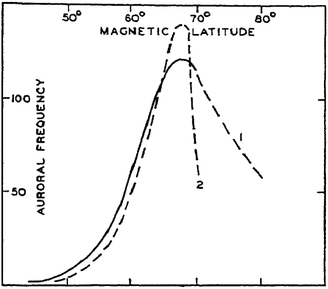


Fig. 35.—Average auroral frequency, observed (*curve* 1 *after Fritz*), theoretical (*curve* 2 *after Hulburt*).

Near the maximum-frequency zone aurorae are of almost daily occurrence; they spread into lower latitudes during magnetic disturbance, the spread being greater for the more intense storms. During relatively calm magnetic conditions there appears to be no uniformity in the diurnal course of auroral display at various stations, the data at any station giving the impression that the aurora depends on the local meteorology of the high atmosphere above the station, such as winds and conditions of excitation of the atmospheric atoms and molecules [813, 818]. During magnetic storms intense, moving, and colored displays are usually more frequent in the evening than in the morning, the diffuse, weak, and quiet forms being more abundant in the morning.

Many of the lines in the spectrum of the aurora have been identified [823, 1327] as emission-lines from nitrogen molecules and oxygen atoms, the prominent green-line at 5,577 Ångstroms originating from metastable atomic oxygen. No helium or hydrogen emissions have been detected. Störmer [836] has called attention to very high auroral streamers of a violet-gray color extending occasionally to an altitude of 1,000 km. These were in a region illuminated by the Sun. Their spectra differed from those of the usual aurorae in the Earth's shadow in that the green-line was relatively weaker than the nitrogen bands [836, 1443].

Ionospheric observations in Northeast Land [1117] (latitude 80° 23′ north, longitude 19° 31′ east) indicated that no special conditions in the ionosphere obtained when the aurora was overhead.

(4) CORPUSCULAR THEORY OF MAGNETIC STORMS

There is no complete corpuscular theory of magnetic disturbance. At various times charged particles from the Sun have been suggested to account for magnetic effects but the suggestions have been either indefinite or shown to be untenable. It has been long recognized [369, 433] that the world-wide increase in H during the first phase of the storm could be occasioned by a sudden existence of an eastward electric current ringing the Earth mainly in tropical latitudes, and the decrease in H during the second phase by a similar westward current. Such ring-currents formed of electrons or positive ions have been postulated [66, 1339] but no investigations were made of the manner of formation or of the stability and disintegration of the rings. The postulates appeared to create more difficulties than they solved.

A corpuscular theory of magnetic storms developed by Chapman [377, 381, 382] did not survive the criticism of Lindemann [410] and was given up by Chapman [377, 381, 382]. The theory assumed that particles of like charge, emitted by the Sun in a beam, plunged into the outer atmosphere and caused a downward movement of the conducting region. By dynamo-action, (45), this induced an eastward current around the Earth which caused the increase in H of the first phase of the storm. Owing to electrostatic repulsion of the charged particles the downward motion was followed by an upward expansion which induced a westward current, the second phase of the storm. However, Lindemann pointed out, making use of an idea advanced by Schuster [436], that a beam of particles with the same sign of charge and of sufficient density to carry the storm-energy could not proceed as a beam for more than one or two solar diameters on account of electrostatic repulsion and could not approach the Earth after the first few sec on account of the charge which the Earth would rapidly acquire.

Chapman and Ferraro [388] attempted to construct another theory on the assumption that electrically neutral streams of equal densities of positively and negatively charged particles are shot out from the Sun.

They envelop the Earth at distances of 50,000 km or more and through their diamagnetism cause the increase in H of the first phase of the storm. As the cloud of charged particles progresses into the terrestrial magnetic field, the positives are diverted westward and the negatives eastward. The idea was entertained that the particles might swing around the Earth and form a westward electrical current which would cause the second phase of the storm. However, the authors concluded that they were unable to follow through the physics of the establishment of the ring-current. Chapman recently remarked [1439], "The whole theory is necessarily both speculative and difficult; probably the most doubtful feature is that relating to the ring-current, the existence and formation of which are still very uncertain." The theory was left in a qualitative and unfinished state. It suggested no explanation of the diurnal storm-variations, nor did it envisage how the particles were to enter the ionosphere to produce changes during magnetic disturbance.

(5) CORPUSCULAR THEORY OF AURORAE*

The well-known corpuscular theories of the aurora of Birkeland, Störmer, and Vegard [835, 845, 851] are confronted with the Schusterian [436] difficulty which they have never got around, as pointed out by Lindemann [410], Swann [1515], and others. Störmer's calculations of the focusing of the charged particles into the auroral zones by the magnetic field of the Earth refer to a single particle, as an electron or an α particle, whereas the auroral theory requires a cloud of particles, and it has been shown [388, 410, 1515] that a stream of electrons or ions, or mixtures of electrons and ions, cannot account for the auroral zone. Chapman and Ferraro [387, 388, 996] concluded,

> A re-examination of the conditions of passage of the stream from the Sun to the Earth disposed of our lingering hope that the stream might carry some small residue of charge which would at least suffice to explain the production of aurorae, by permitting the stream to be deflected in the same way as separate corpuscles are in Störmer's theory (although to a smaller extent); our work confirmed Lindemann's conclusion that the only admissible kind of stream is one that is electrostatically neutral to a very high degree of approximation.

(6) ULTRAVIOLET-LIGHT THEORY—GENERAL ASSUMPTIONS

The ultraviolet-light theory of magnetic storms and aurora was developed in detail, largely quantitatively, in a series of papers [406, 418, 420, 818]. The more important physical ideas are described here. Referring to Table 3, above a level of about 300 km there are approximately 10^{16} molecules in a one-cm^2 vertical column of the atmosphere. Above this level they experience practically no collisions but dance up and down, receiving upward thrusts from impacts from below and falling back under gravity. This is the outer fringe or spray of the atmosphere. The 10^{16} molecules experience 10^{14} collisions sec^{-1} at the 300- or 400-km level. For a temperature of 360°K ordinary impacts impart velocities of order one km sec^{-1} which rarely send the particles above 2,000 km. It is assumed that during solar quiescence—that is, no magnetic storms or aurorae—10^8 of the 10^{14} impacts are collisions of the second kind with excited atoms and molecules which give the particles velocities as great as ten km sec^{-1}. They reach heights of 40,000 to 80,000 km in three to six hours and if un-ionized fall back to the Earth in various orbits depending on the angles of projection, as shown in Figure 36.

---

* This section has been made very brief in order to avoid repetition of the excellent discussion by Vegard on the same subject in Chapter XI.

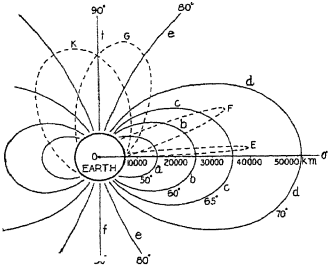


FIG. 36.—Curves *a*, *b*, *c*, etc., are magnetic lines *of force of magnetic field of Earth, number near each* curve being magnetic latitude where line touches the Earth; curves *E*, *F*, *G*, and *K* are the orbits of particles projected from the Earth with velocity ten km sec^{-1} at angles to the vertical of 1°, 22°, 45° and 60°, respectively.

It is assumed that the high-flying particles are ionized by the ultraviolet light of the Sun in three to six hours. Once ionized they follow along the lines of magnetic force into the outer atmosphere of high latitudes and give up their energy in the form of auroral light and magnetic effects. The flux of energy into various latitudes was calculated and is plotted in the dotted curve 2, Figure 35; it is in agreement with the observed curve 1. Under the assumptions just outlined the energy transported into the auroral zones is 5×10^{13} ergs sec^{-1} which is perhaps sufficient for a quiet aurora but not so great as the 10^{15} ergs sec^{-1} of a strong auroral display [406, 418].

It is assumed that the Sun when active sends out a blast of ultraviolet light for half an hour. For example, if 1/10,000 part of the solar surface were to emit black-body radiations at temperature 30,000°K, the solar constant would be increased by 0.74 per cent and the solar energy at wave-lengths 3,500, 4,000, 5,000, and 6,000 Ångstroms by 3.2, 1.7, 0.75, and 0.32 per cent, respectively. Corresponding values which are observed [1514] in the short-interval (an hour or so) variations of the solar energy are roughly 1, 8, 2, 1, and 0.2 per cent, and often more. The energy in the ultraviolet regions 3,000 to 2,000, 2,000 to 1,000, and 1,000 to 0 Ångstroms would be increased by factors of 1.5, 10^2, 10^5, respectively. Calculations such as the foregoing based on the assumption of black-body conditions can be regarded as only illustrative approximations, and perhaps very distant ones, for line-emission and absorption undoubtedly play a predominating rôle. The energy increases the ionization of the high atmosphere and the high-flying spray and causes heating, outward expansion, and winds. These in turn give rise to aurorae and magnetic disturbances.

(7) ULTRAVIOLET-LIGHT THEORY OF AURORAE

In the spectrum of the ultraviolet solar flare the wave-lengths shorter than the limit of the principal series of a given atom are probably the most effective in ionizing the atom whereas somewhat longer wave-lengths would be expected to cause excitation of the atom. In general, various types of solar flares may be assumed, such as (1) flares containing mainly the excitation wave-lengths, (2) flares which contain both the excitation and ionizing wave-lengths in varying intensity. A flare of type 1 would produce many excited atoms; these give rise to high-flying atoms or molecules which when ionized fall to the polar regions and cause aurorae. Since such a flare does not produce many ions in temperate latitudes, there will be no strong world-wide magnetic disturbance. Therefore in this case there may be a strong auroral display in polar latitudes unaccompanied by a magnetic disturbance in temperate latitudes of sufficient intensity to be called a storm. Examples of this were the strong auroral displays seen on the Antarctic Continent on April 20 and 27 and June 18–21, 1908, at Cape Royds on June 3, 1912, and at Cape Denison on May 29, June 19, and July 7, 1913. The magnetic conditions at the stations were disturbed at these times [73], but in temperate latitudes no magnetic storms were recorded on or within a few days of these dates. Many brilliant auroral displays with no temperate-zone magnetic disturbances were recorded by the *Maud* Expedition [75] during the years 1922–25 in the Arctic Ocean north of Siberia.

A flare of type 2 would, in addition to producing many ions, give rise to many high-flying particles which, because of the unusual intensity of the ionizing wave-lengths, would be ionized quickly before they had time to attain great heights. They would not reach polar areas but would move along the magnetic lines of force of the Earth's field to high temperate latitudes in sufficient concentration to give an auroral display. Therefore, strong magnetic storms would be expected to be accompanied by aurorae in high temperate latitudes and the stronger the storm the more spreading of the display into lower latitudes there would be. This spreading effect has long been recognized [432]. Temperate-zone auroral displays were observed by Barnard [799] at the Yerkes Observatory on about 140 nights in the years 1902–09; magnetic storms accompanied 120 of the displays. On the nights when there were no storms, the auroral manifestations were feeble and it is possible that magnetic disturbances may have occurred which were too weak to be listed as storms.

A particle ejected upward from the atmosphere with a velocity around ten km sec^{-1} reaches 40,000-km levels in about three hours. If it is ionized there by the sunlight, it falls to polar regions, requiring several hours for the descent, the exact time depending on the pitch of the spirals of its path and on its velocity at the instant of ionization, provided that the only influences which act on the ion are gravity and the magnetic field of the Earth. Other agencies may be thought of, such as light-pressure, electric fields, etc., but whether these are important cannot be said. After falling to the 300- or 400-km level further descent of the ionization is by diffusion through the atmosphere, and calculation [406, 418] shows that three to six hours are required to reach a 100-km level. If the same ultraviolet flare which causes the polar ion-migration, and hence the aurora, also causes heavy ionization in the upper atmosphere, and hence a magnetic storm, the aurora should appear several hours after the initiation of the storm. Since the ion-migration to the poles is, or may be, suppressed while the flare is at its greatest intensity, one might expect the delay in the appearance of the aurora in high polar regions to be greater for a long-continued intense magnetic storm than for a shorter storm.

The auroral observations recorded in the journals of the British and Australasian Antarctic Expeditions [72, 73] and of the *Maud* Arctic Expedition [75] furnished data in keeping with the foregoing theoretical inference. In Figure 37 are plotted the auroral data at Cape Denison, Antarctica, and the world-wide intense (No. 3) magnetic storm which began at 2 o'clock, September 17, 1912. The aurora occurred about 40 hours after the storm began. Altogether 11 magnetic storms were found for which the Antarctic and Arctic auroral data were sufficiently complete to permit figures similar to Figure 37 to be made. The results indicated [406, 418] that the polar auroral displays began about a day after the commencement of the storm in low latitudes and, although the data were too few for great certainty, that the time-interval between the display and the storm was longer for the more intense storms. Davies [809] in an extended statistical analysis of the auroral observations of the First Byrd Antarctic Expedition presented further confirmation of the delay-effect in concluding that, "comparison of auroral character-numbers for days with the international magnetic character-numbers shows marked evidence for the occurrence of an auroral maximum on the same day or one day after a maximum in the magnetic character-curve."

No reference has thus far been made to the production of the auroral spectrum in the laboratory. Kaplan [821] has been able to reproduce many features of the auroral spectrum in weak discharges and afterglows in oxygen and nitrogen and to obtain much information about the excitation-processes. In the end the experiments will lead to very important knowledge of the physical state of the atmosphere during aurora.

Finally, it may be remarked that all theories of the aurora are geometrical theories in that they merely offer mechanisms whereby energy is supplied to auroral regions. They make no suggestion concerning the manner in which the energy is transformed into auroral light. A complete theory should do this and will require among other things complete knowledge of the energy-levels, metastable states, and transition-probabilities of the atmospheric atoms and molecules as well as of the exact processes which give rise to the auroral light. Further, the idea has obtruded itself at all times that the emission of the auroral light may not depend simply upon an energy-influx carried by ions but may require in addition that the atmosphere into which the ions fall be in a suitable and perhaps critical condition, such condition being an erratic function of wind-currents and states of excitation of the atoms and molecules.

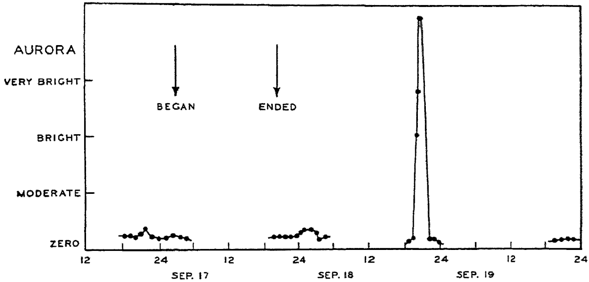


FIG. 37.—Aurora intensity at Cape Denison, Antarctica, and magnetic storm of September 17, 1912.

(8) ULTRAVIOLET-LIGHT THEORY OF MAGNETIC STORMS

The assumed solar flare of one ten-thousandth part of the solar surface, at 30,000° would send 10^{22} ergs to the Earth in one sec, which is roughly the total energy of an average magnetic storm of one-day duration. Thus a smaller or less intense flare lasting for more than one sec would supply the storm-energy. The light from the flare is mainly in the ionizing wave-lengths below 1,500 Ångstroms and increases the ionization of both the long and short free-path regions over the day hemisphere; flares with different spectral characteristics may increase the long and short free-path ions by different amounts. An increase in the daylight long free-path ions increases the eastward 5×10^6-amp current which girdles the Earth. H then increases and V decreases as in the first phase of the storm. An increase in the daylight short free-path ions causes an increase in the electrical conductivity and hence an increase in the westward daylight current in the short free-path ion-region. This reduces the eastward 5×10^6-amp current and therefore amounts to a westward storm-current girdling the Earth; H is decreased and V is increased as in the second phase of the storm.

There is an additional effect which is common to all types of flares, namely, a heating of the high atmosphere above the, say 100-km level. The heating causes an outward expansion of the outer atmosphere which produces two reactions, a dynamo-effect and an "engulfing" effect. The dynamo-effect results from the upward movement across H and is a maximum in tropical latitudes where H is approximately horizontal. It gives rise to an induced westward electric field and causes a westward current around the Earth which reduces H. An upward velocity of the short free-path region of Figure 25 of ten km hr^{-1} reduced H by about 100 γ at the equator. The engulfing effect, also a maximum in tropical latitudes, depends on the fact that where H is approximately horizontal the long free-path ions can move only a short distance across H between collisions and are therefore hindered from moving upward freely with the neutral particles of the expanding atmosphere. Thus, after the initiation of the storm many of the long free-path ions find themselves in a mounting tide of air-molecules; their free paths are shortened and they become short free-path ions. Since the ions experience many collisions before being lost by recombination, the daylight short free-path ions are increased at the expense of the long free-path ions with a consequent effective westward storm-current.

We may picture the sequence of events in the world-wide storm of Figure 32 as follows: The solar flare by its ionizing energy first increases the long free-path ions which enhances the eastward current and increases H to a value above normal as in the initial phase of the storm. In the second phase the heating effects of the flare make themselves felt, the high atmosphere expands, the ionized layers move upward, and H decreases for a few hours. When the layers cease their upward movement, H would increase to its previous value above normal were it not for the fact that in the meantime the engulfing effect has reduced the long free-path ions, so that actually H decreases to a value below normal. Thereafter H increases slowly to its normal value as the flare dies away, the storm-ionization diminishes, and the atmosphere settles down to its quiet-day condition.

Magnetic storms which do not begin with an increase in H, and which consist of only the second phase, are fairly common; for example, the third curve of Figure 31. In these cases we may suppose that the flare emits mainly energy which heats the high atmosphere and produces mainly short free-path ionization. Storms made up of only the first phase are less frequent; they require a flare which increases the long free-path ionization without much heating. Irregular and local storm magnetic variations may be attributed to motions of the ionization due to winds and to effects of induced currents in the Earth.

The diurnal magnetic storm-changes of Figure 33 are attributed to the effects of the high-flying ions which descend into polar regions. Assuming that the Earth as a whole carried no excess charge, it was shown [406, 418] that particles sprayed out from the noon meridian of low latitudes fall as ions into the 300- to 400-km levels of high latitudes at 1 to 2 P.M.; they are slowed up and descend by diffusion the next 200 km in three to six hours. Being long free-path ions they set up eastward magnetic gravitational drift-currents which, if the conductivity of the high atmosphere varies with the zenith-angle of the Sun approximately as given by (48), spread into current-sheets as sketched in Figure 38. This current-system gives rise to the diurnal storm-changes of Figure 33. The theory was shown to be acceptable quantitatively [406, 418]. At the same time winds in the ionized high atmosphere blow across the twilight zones from sunlit to dark areas and cause strong irregular magnetic agitation. It seems possible that the increase of magnetic-disturbance energy with latitude brought out in Figure 34 may be due mainly to the effect of winds.

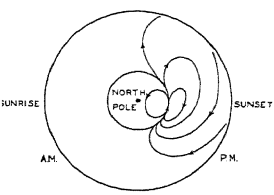


FIG. 38.—Theoretical currents in the high atmosphere which cause the diurnal magnetic storm-variations.

The recent observations of the simultaneity of incipience of radio fade-out, ionospheric change, magnetic perturbation, and solar eruption [1109] support the ultraviolet theory to the extent that they prove that a certain special type of magnetic disturbance is caused by radiation from a solar outburst which travels approximately with the velocity of light. However, the solar flare or eruption which causes the world-wide magnetic storms will remain difficult to detect by the methods in use at present, for if such detection were easy it would have been accomplished long ago. The wave-lengths of the ultraviolet flare, which according to the theory give rise to the magnetic storm, are shielded by the atmosphere from direct observation, and hence are invisible. Only if these are accompanied by longer wave-length radiations, and there is no compelling reason why they should be, can the flare be seen. Therefore it may turn out that detection of the flare by observation of the solar surface may fail in many cases. Further, the flare may be only a very minute single pin-point on the solar disk, or a number of even smaller pin-points.

In this connection an interesting program of observations of solar prominence spectra, initiated in 1928, has been carried on by Perepelkin [1497] at Poulkovo Observatory. The ratio, i, of the intensity of the Balmer hydrogen line, H_ϵ, to that of the calcium-resonance line, H, was found to vary with magnetic activity, W_D, as shown in Figure 39, where W_D was the diurnal declination-range at Pavlovsk. The correlation between i and W_D was better than between the relative sunspot-number and W_D. This was a new important experimental fact quite apart from any theory. Perepelkin pointed out that unfortunately the new index, i, referred only to the edge of the solar disk where the prominence spectra were obtainable. The mean value of i was practically the same for various heliographic latitudes but the individual values varied from prominence to prominence, leading to the supposition that the causes of the change in i should not be looked for on the Sun as a whole. A theory was outlined which adopted the hypothesis of the existence on the solar surface of spots rich in ultraviolet radiation. In the case of constancy of the relative concentrations of hydrogen and calcium atoms such radiations increase the intensity of H_ϵ more than that of H and hence increase i.

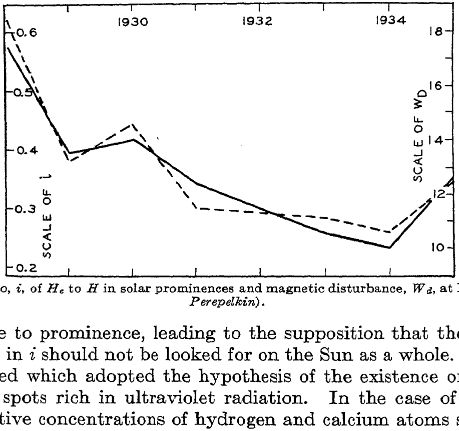


FIG. 39.—Ratio, i, of H_ϵ to H in solar prominences and magnetic disturbance, W_d, at Pavlovsk (*after Perepelkin*).

(9) BEAM- AND FLARE-THEORIES OF SOLAR OUTBURSTS

Concerning the form of the emission from the Sun which gives rise to magnetic disturbance two theories have been advanced, that the solar emission is in a narrow beam, as from a searchlight or a shotgun, and that the emission is in a wide flare, as from a volcano. The statistics of magnetic storms [272, 290, 298] have shown that disturbed conditions often tended to recur after intervals of about 27 days, and to explain this Maunder [422] suggested that the solar emission came from a restricted area of the solar surface in a narrow beam which rotated with the Sun.

The synodic rotation-period of sunspots is 26.9, 27.3, and 28.3 days at heliographic latitudes 0°, 15°, and 30°, respectively; the periods of the reversing layer are about two per cent less. Therefore, if the period of the beam is that of the solar surface, the beam must come from a solar latitude of about 15°. On the assumption that the characteristics of a magnetic storm are somehow directly connected with the beam, the width of the beam is about 13° for a storm lasting one day and 1° for a two-hour disturbance, provided the emission travels approximately with the velocity of light; if the velocity is less, the beam-width is less. A sudden commencement calls for a beam of exceedingly sharp forward edge. These requirements of the beam are stringent and evoked the shining remark from Chree [422], "The theory advanced hardly touches the physical side of the problem, but it is clear and definite so far as it goes, and is obscured by no mystifications of language. It is certainly incomplete, and may be wholly erroneous, but it is exceedingly suggestive. . . . "

The rotating-narrow-beam theory has met with difficulties in several directions. The surface rotation of the Sun increases by about six per cent from minimum to maximum of sunspots [1458, 1489], whereas no systematic lengthening or shortening of the 27-day recurrence-interval could be detected for groups of years of many or few sunspots or for high- or low-sunspot latitudes [290, 298].

Terrestrial magnetic activity has long been recognized to undergo a seasonal variation according to a cosine-law approximately with maxima at equinox and minima at solstice, the storm-frequencies being about twice as great at the maximum as at the minimum [417]. The narrow-beam theory sought to explain the seasonal changes by the tilt of the solar axis with respect to the Earth, or in other words by the seasonal variation of the heliographic latitude of the Earth [383, 396]. Three separate rigorous tests of the idea by Bartels [272] all led to failure; his paper should be consulted for details. Maris [417] carried out detailed calculations based on the wide-angle ultraviolet-flare theory that have led to a reasonable explanation of the seasonal magnetic effect based on the tilt of the Earth's axis with respect to the Sun. At the same time he pointed out that probably all terrestrial magnetic disturbances are not of solar origin, but that some may arise from the passage of the Earth through debris of planetary space.

Maris and Hulburt [419] looked to comets for evidence bearing on the width of the solar emission. They argued that if the same emission which caused the terrestrial magnetic storm and aurorae fell on a comet it might cause changes in the comet. Many cases of apparently lawless and erratic behavior of comets, some famous in comet history, have been observed, such as a sudden brightening, a splitting into pieces, or the emission of a new tail. It was found that in general the comet events followed closely after a strong magnetic disturbance. A plot of the positions of the Sun, Earth, and comet at the epoch of 28 comet events showed that the average angle of the solar flare was about 90°. A direct association of comet events and terrestrial magnetic perturbation was incompatible with the narrow-beam theory.

It is concluded that what evidence there is supports the wide-angle-flare hypothesis and is unfavorable to the narrow-beam hypothesis. The conclusion leaves the recurrence-tendency of magnetic storms without an explanation. This may be provided by the *ad hoc* assumption that the flare puffs out with the recurrence-period owing to solar pulsations of some sort [419]. Thus the two views are equally novel in that they call for unanticipated characteristics of the solar outburst, the rotating-beam theory requiring a physically strange narrow beam and the wide-puff theory a recurrent geyser-action, which by coincidence has a period about the same as that of the rotation of the Sun.

IX. ZODIACAL LIGHT AND GEGENSCHEIN

(1) Observational data

Shortly after sunset when the evening twilight has gone, the zodiacal light appears as a faint cone of light in the west rising upward from the horizon; there is a similar cone in the east before dawn twilight [1461]. At their apexes the cones narrow to a band which extends across the sky from one apex to the other. Thus the phenomenon is spoken of as a "band" of luminosity. The band lies closely, but not exactly, along the plane of the ecliptic. It is usually less bright than the Milky Way and may be seen on any clear night when there is no disturbing illumination such as the Moon, planets, the Milky Way, or artificial lights. At an angle of 30° from the Sun, the closest angle to the Sun at which the light can be seen when observed in the eastern or western sky, the band is about 40° wide [1457]. The width, of course, is rather indefinite, for the band is brightest near its center and fades into obscurity at the edges. Newcomb [1490] and Barnard [1430] in north latitudes around 45° during the midnight hours of the summer solstice observed a glow passing from the west to the east along the north horizon. They concluded that this was the zodiacal band, for it could not have been ordinary twilight because the Sun was more than 18° below the horizon, and that therefore the band was about 70° wide along the Sun's axis. With increasing angular distance from the Sun the band decreases in width and in brightness. At 90° from the Sun it is about 20° wide and at 150° about 10° wide. At 180°, the point directly opposite the Sun, there is a faint knot of luminosity, sometimes appearing as a swelling in the zodiacal band, called the "Gegenschein." Figures 40-*A* and 40-*B*, respectively, are photographs of the zodiacal light taken by Pachine [1492] in Russia, January 28, 1911, and by Brunner in Switzerland, March 21, 1927. In the case of Figure 40-*A* the light was unusually bright.

To the instructed observer at sea and in open country the zodiacal light and gegenschein are striking apparitions; they appeal to curiosity and imagination. However, the phenomena have not received great attention from astronomical observatories chiefly because large telescopes are of no use in examining such diffuse and faint luminosities. The unaided eye is the best instrument for the purpose. This may explain why the observations of Jones [1469], Chaplain, U.S.N., are the most complete and extensive available. During a voyage on the Pacific Ocean from April 2, 1853, to April 22, 1855, he observed the zodiacal light every night, weather and other conditions permitting, and sketched on a chart of the heavens the light as he saw it.

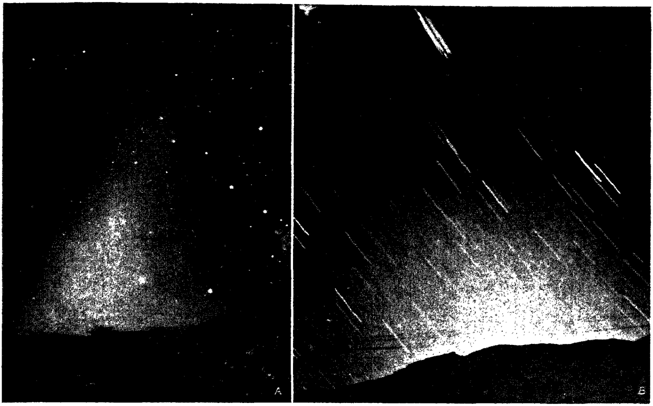


FIG. 40.—Photographs of the zodiacal light (*A*) January 28, 1911 (*after Pachine*); (*B*) March 21, 1927 (*after Brunner*).

In 1874 Wright [1522] observed that the zodiacal light was partially polarized, about 15 per cent.

Early spectroscopic observations with low dispersion appeared to indicate that the zodiacal spectrum was similar to that of sunlight [1445]. More recent observations [1443, 1500, 1501, 1512] with high-power instruments have shown that the zodiacal emissions differ from those of the Sun and are similar to those of the night sky and the aurora. The night-sky spectra were of course always superimposed on the zodiacal spectra. A comparison of the zodiacal plus night-sky spectra with spectra of the night sky alone showed that they both contained the same lines of oxygen, nitrogen, and unknown origin and that the two spectra differed mainly in that the zodiacal spectrum, which averaged about two or three times as intense as the night-sky spectrum, had relatively less of the auroral green-line, λ 5577. The spectrum of the gegenschein has not been observed.

It has been recognized for over a century that the zodiacal light is at times variable in intensity, the entire body of the light alternately strengthening for a few minutes and weakening again. That the zodiacal light is often unusually intense during epochs of strong aurorae has been known for a long time. A comparison of such abnormalities, recorded by Jones and others, with the data of magnetic observatories led to the conclusion that they occurred during epochs of magnetic disturbance [1461]. Similarly, variations in brightness of the gegenschein [1430, 1442, 1490] fell in with magnetic activity, although observations of the gegenschein were too few to establish the connection with certainty.

(2) PLANET-DUST THEORY

The planet-dust theory, as presented in text-books [1507], assumed that there are dust-particles in a flat lens-shaped region with the Sun at the center spreading out in the plane of the ecliptic well beyond the orbit of the Earth. The particles were not molecules of a gas, for, owing to diffusion and light-pressure, molecules would not stay near the plane of the ecliptic. The particles were considered to be small solid bodies each moving in its independent orbit around the Sun. It was suggested that they were small meteoroids of the solar system, possibly remnants of the spray and dust from the large splash which inaugurated our planet system [1467]. The particles were assumed to reflect the sunlight, particles one mm in diameter and five miles apart of albedo 0.07, the albedo of the Moon, being sufficient to account for the observed zodiacal luminosity. The assumption was in keeping with the fact that light reflected from minerals such as granite and clay was partially polarized [1522].

Since the zodiacal light undergoes fluctuations in intensity, it follows that all of the light cannot be reflected sunlight. For the sunlight, at least in that portion of the spectrum accessible to us, does not fluctuate very much, the short-period (a few hours or a day) variations [1514] of the solar constant being usually less than ten per cent, whereas the variations in the zodiacal-light intensity, although not measured, would perhaps be of the order of hundreds of per cent. Therefore the planet-dust theory, if it be retained at all, requires some fundamental modification not heretofore contemplated. Furthermore, the theory is confronted with the fact that the zodiacal spectrum is not that of reflected sunlight.

The meteorite theory of the gegenschein of Gyldèn and Moulton [1486] arose from a particular solution of the problem of three bodies. Small particles with correct velocities entering a region along a line from the Earth opposite the Sun execute nearly closed orbits and remain in the region for a considerable length of time. The density of particles in the region would therefore be greater than in surrounding space. They would reflect sunlight and cause the gegenschein if there were enough of them.

(3) ATMOSPHERIC THEORY

The atmospheric-ion theory of the zodiacal light and the gegenschein was based on the conception of the high-flying atmospheric spray of the aurora and magnetic-storm theory of Section VIII. The theory was given quantitative formulation throughout; the original paper [1461] should be consulted for details. It was assumed that fast-flying atoms or molecules are sprayed out in all directions from the sunlit hemisphere of the Earth which, after a number of hours, are ionized by the ultraviolet light of the Sun. Under the action of solar-radiation pressure and the Earth's magnetic and gravitational fields, ions at levels beyond 30,000 km form a sort of oblong ring around the Earth approximately in the plane of the ecliptic. The ions absorb sunlight in the far ultraviolet region of the spectrum and re-emit a portion of the absorbed energy as visible light. This is the zodiacal light. The portion of the ion-ring away from the Sun streams away in a long tail. Viewed end-on, this is

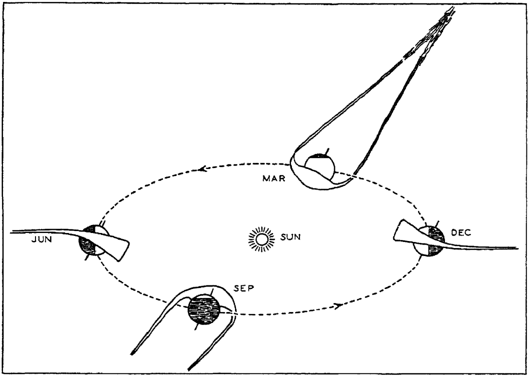


FIG. 41.—Zodiacal ion-ring according to the atmospheric theory.

the gegenschein. The results of the theory are represented in Figure 41; the Figure is not drawn to scale. On the daylight side of the Earth the zodiacal ion-ring is wide and follows the plane of the Earth's equator. On the night side the ring is narrow, is warped off the equatorial plane roughly on to the ecliptic plane, and trails off to a great distance.

Being fluorescent light, or perhaps an afterglow, the spectrum of the emissions from the zodiacal particles should be different from that of sunlight. Variations in the stimulating solar ultraviolet light, as the solar ultraviolet flare of the aurora and magnetic-storm theory, will cause changes in the zodiacal brightness. The warped shape of the zodiacal ring (Fig. 41) furnished an explanation of the fact that at spring equinox the evening cone is to the south and the morning cone to the north of the ecliptic, with a reversed position of the cones at autumn equinox. The theory encountered a difficulty in explaining the 15 per cent polarization of the zodiacal light, for fluorescent radiation would not necessarily be supposed to be polarized, although it may be. The difficulty was put aside by the expression of the wish that the polarization observations be repeated.

X. ATMOSPHERIC OZONE

It has long been known that the spectrum of the Sun ceases rather abruptly at about 2,900 Ångstroms in the ultraviolet as though caused by some absorbing material between the terrestrial observer and the Sun. Small changes in the ultraviolet-spectrum limit with the solar zenith-angle indicated that the material was in the atmosphere of the Earth. Early researches by Fabry and Buisson [1237, 1238] on the absorption-characteristics of ozone demonstrated that the atmospheric material was ozone in total thickness of about three mm of O_3 at normal temperature and pressure and indicated that the ozone was at a level about 40 km. More recent investigation, described below, has shown that most of the ozone is probably situated in the region below 50 km with a maximum density at a height between 20 and 30 km. An excellent survey of the atmospheric-ozone problem has been given by Penndorf [1249]. We present here an outline of the facts as far as they are known and a brief description of the theory.

The distribution over the Earth of atmospheric ozone was determined by a number of observers under the direction of Dobson [1236]. The results are given in Figure 42 and show that the amount of ozone in a vertical column of the atmosphere undergoes an annual variation with a maximum near the spring equinox and a minimum near the autumn equinox, the amplitude of the annual variation increasing from zero at the equator to about 1.3 mm of O_3 at normal temperature and pressure at about 68° latitude. The ozone-values increased with the latitude from about two mm at the equator to 3.5 mm at 60° in March and to 2.5 mm at 60° in October. Approximate ozone-measures by means of solar and lunar spectra at Little America, Antarctica [1242], latitude 78°.6 south, indicated about 2.8 mm in the summer on November 13, 1929, and January 25, 1930, and roughly the same amount near midwinter on July 18, 1929.

Regarding the change in ozone with the sunspot-cycle there are few long continued series of ozone-data. The yearly average ozone-values obtained by Fowle [1239] at Harqua Hala, Arizona, latitude 33°.8 north, and at Table Mountain, California, latitude 34°.4 north, are plotted together with the yearly average Wolfer sunspot-numbers in Figure 43. From 1921–28 the ozone appeared to vary with the sunspots, but the correspondence did not appear to be maintained from 1928–34. At Canberra, Australia [1243], the ozone during 1932 was slightly above its value for 1929, 1930, and 1931. The suggestion was made that either the ozone or the spectrographic observations might have been affected by an outburst of volcanic dust in the atmosphere in 1932.

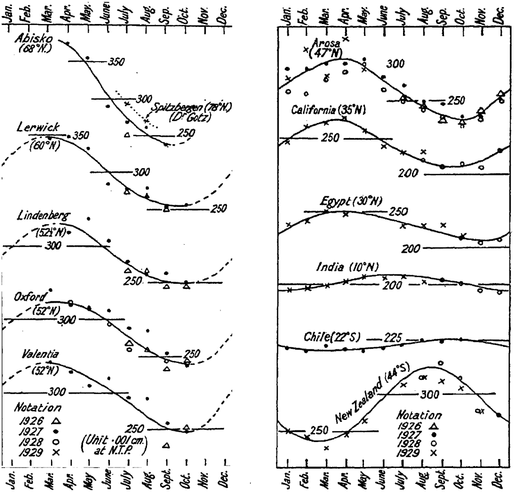


FIG. 42.—Variation of ozone with latitude and season (*after Dobson*).

It is not known with certainty whether there is a diurnal variation in the ozone-content of the atmosphere above any station. A few data [1236] indicate that a diurnal variation, if it exists, is small.

A connection between ozone and sea-level barometric changes is complicated and has not been established with certainty. From data of six ozone-stations in Europe, Dobson [1236] concluded that the smallest amount of ozone occurred to the southwest of a barometric high and that the passage of a barometric low over a station was accompanied by an increase in ozone-content. Meethan [1246] found that variations in ozone showed a close correspondence with the height of the tropopause; roughly, a decrease in height of tropopause of one km was accompanied by an increase of 0.1 mm in thickness of ozone. In general, since most of the ozone lies between 15 and 35 km its variations would be expected to be correlated with changes of pressure and winds in the stratosphere rather than in the troposphere, and at the present time the relation between stratospheric and tropospheric weather cannot be said to be completely known and understood.

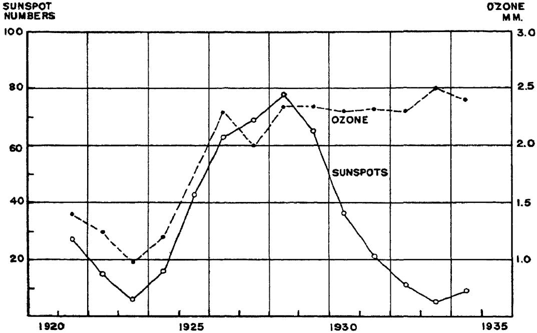


FIG. 43.—Variation of ozone with sunspots at north latitude 34° (*after Fowle*).

Direct measurements near the ground and on mountains have indicated the presence of ozone in the lower atmosphere. Various European data were summarized and averaged by Penndorf [1249], and from his average curve the ozone-thickness per km of air was 12, 17, and 28 $\times 10^{-3}$ mm at altitudes zero, one, two, and three km, respectively. The values are probably not representative of world-wide conditions, for the ozone near the surface of the Earth may be supposed to vary within wide limits with weather and with dust and impurities in the lower air.

Balloon-flights have enabled the direct measurements to be extended to 30 km in the case of Regener's unmanned balloon [1250] and to 22 km in the case of *Explorer II* [1298]. The results are shown in Figure 44. The Regener flight occurred near Stuttgart on July 31, 1934, the total thickness of ozone being 2.6 mm. The flight of *Explorer II* took place in South Dakota, United States, on November 11, 1935, the total thickness of ozone being 1.9 mm. The ozone-curve of this flight in Figure 44 was obtained from direct measurements up to 22 km, the highest altitude reached by the balloon, and was extended to heights above 22 km by means of sky-light spectra.

A new method, and at present the only one, for evaluating the vertical distribution of ozone from measurements on the ground was developed by Götz [1240, 1241], the method being based on his discovery of the "inversion"- (Umkehr-) effect. The method is briefly as follows: Let the intensities of two wave-lengths, λ_1 and λ_2, of the solar spectrum be i_1 and i_2, respectively, λ_1 being considerably absorbed by ozone and λ_2 absorbed very little or not at all; for example, $\lambda_1 = 3{,}110$ Ångstroms and $\lambda_2 = 3{,}290$ Ångstroms. When the ratio, i_1/i_0, was determined from spectra of the zenith-sky for various values of ζ, the solar zenith-angle, the value of i_1/i_2 was found to decrease with increasing ζ to a minimum at about $\zeta = 85°$ and then to increase. The march of the (i_1/i_2)-curve was termed the "Umkehr"-effect. The procedure of determining the approximate vertical distribution of ozone from the (i_1/i_2)-curve and the value of total ozone-thickness outlined by Götz consisted essentially in assuming a number of ozone-distributions, calculating the respective (i_1/i_2)-curves, and continuing the process until a distribution was found which was in agreement with the observed curve. The distribution thus obtained was not mathematically unique, but its uncertainty could be confined within limits set by the errors of observation. Chapman [1235] has given illustrations of the computations with considerable numerical rigor. As yet all results have been derived on the assumption of a flat Earth, with

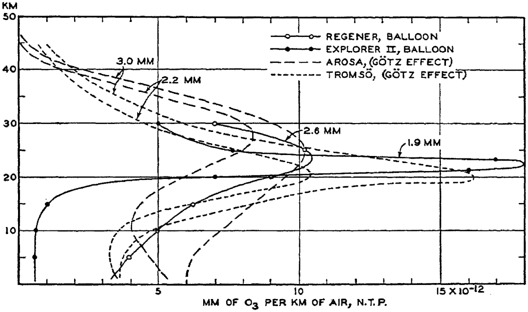


FIG. 44.—Vertical distribution of ozone.

the neglect of secondary scattering and of the refraction of solar rays in the atmosphere; it was considered that the approximations led to no serious errors. On the experimental side the method requires an atmosphere free from haze and clouds and is applicable mainly near sunrise and sunset.

Results obtained from measurements of the inversion-effect at Arosa [1240, 1241] and at Tromsö [1247] are given in the dotted curves of Figure 44 for two values of total ozone-thickness. The observations were carried out at Arosa during 1922–33 and at Tromsö during May and June, 1934. The curves of Figure 44 comprise about all that is known at the present time of the vertical distribution of ozone.

The more important theories attribute the origin of atmospheric ozone to the photochemical action of sunlight in the oxygen of the terrestrial atmosphere. The theories of Chapman [1233, 1234], Mecke [1244, 1245], and Wulf [1254, 1255, 1256, 1257] may be referred to. They are similar in showing that a bank of ozone, in photochemical equilibrium, with a maximum density at some height above the Earth is formed by sunlight passing into the terrestrial atmosphere, if the light be assumed to be absorbed exponentially, or approximately so, and to give rise, directly or indirectly, to ozone in proportion to (or some function of) the energy absorbed. The theories differ in details of assumptions of the various photochemical processes of the formation and dissociation of ozone and oxygen. Probably the theory of Wulf is the most complete and detailed. He made use of the absorption-coefficients of oxygen and ozone as far as they are known and derived an ozone-distribution with a maximum between 20 and 30 km in agreement with observation. The observed amount of ozone appeared to be in reasonable accord with that calculated from existing photochemical data on the assumption that the solar-energy curve in the ultraviolet below 2,900 Ångstroms was that of a black body at a temperature 6000°K. At present no clear explanation has been offered of the spring maximum and the autumn minimum in the ozone-content of the atmosphere. It seems probable that the origin of these variations, as well as of others, is to be sought in winds and meteorology of the air above 20 km.

CHAPTER XI

THE AURORA POLARIS AND THE UPPER ATMOSPHERE

L. VEGARD

Oslo University

I. INTRODUCTION

The northern lights or the Aurora Polaris are luminous phenomena essentially associated with the polar regions, characterized by sudden and irregular appearance and by a variety of distinct forms which usually undergo rapid changes of intensity, position, and color. Naturally, so conspicuous a luminescence has attracted much attention and its study is as old as natural science itself. From the beginning of the eighteenth century when important observations and theoretical work were undertaken by authorities like Halley, Mairan, Hiorter, and Celsius, to the present day, much skill and labor have been devoted to the study of the aurorae and allied phenomena. The present article does not contemplate a historical account of the earlier investigations within this field, but rather attempts to give a picture of the present standpoint of our knowledge regarding auroral phenomena and their most important relationships.

The more outstanding facts fall into two groups. One group includes those facts essential to the question regarding the primary cause of aurorae and auroral theory. The second group concerns the luminescence itself, its extension, intensity-distribution in the atmosphere, and its physical properties. In the second group is the auroral spectrum with its interpretation and its bearing on the composition and physical state of the upper atmosphere; particular attention will be given this group.

However, it is evident that all phenomena are more or less intimately connected and that the study of the luminescence may lead to results which have important bearing on the cause and origin of the northern lights and related phenomena. In order, therefore, to give a fairly complete picture of the auroral problem, it is intended to include the more important facts and relationships and a short outline of those auroral theories which are still earnestly discussed among scientists. For those who might be interested in the historical side of the auroral work, reference may be made to monographs of H. Fritz [812], of A. Angot [796], and of Vegard [844, 848, 1364].

II. SPACE-TIME DISTRIBUTION OF THE AURORAE AND THEIR SOLAR AND TERRESTRIAL RELATIONSHIPS

(1) Typical forms of the aurorae

The northern lights appear in a great variety of forms. It has been customary and very useful in the description of an auroral display to classify the forms into a limited number of types. Various observers may differ with regard to details, but most will agree in the following classification:

(*a*) *Quiet forms*

(1) *Auroral fog,* that is, haze of luminescence without definite limits.

(2) *Quiet arcs,* which have fairly sharp limitation downward, usually extending across the sky in a direction typical for the locality.

(3) *Quiet luminous bands,* usually extending in the same direction as the arcs and often divided by dark intervals so as to take the appearance of cirrus clouds; often they are simply arcs passing near the zenith.

(4) *Pulsating aurorae,* belonging to the quiet type in so far as the outlines of the luminescence may keep fairly constant for several minutes, but the intensity undergoes very marked periodic changes with periods of say eight to ten sec. At the time of minimum, the intensity may be reduced nearly to zero. The luminescence has usually the form of areas of most curious and irregular shapes.

(*b*) *Moving types*

(5) *Drapery-shaped arcs,* or arcs with a radiant structure, extending in nearly the same direction as the arcs, but thinner and more sharply limited. The long band may move forward and backward and perform a kind of wave-motion. Light-waves pass along the bottom edge and give the impression that parts of the bottom edge are jumping up and down—"merry dancers."

(6) *Draperies,* rapidly moving bands with the appearance of thin curtains with pronounced radiant structure.

(7) *Isolated rays or ray-bundles.*

(8) *The crown,* formed when draperies and ray-bundles appear near the magnetic zenith. The parallel ray-streamers seem to diverge from the same point in the sky (the radiation-point), the position of which determines the direction of the streamers.

(2) Direction of the auroral streamers

The auroral streamers are known to follow approximately the lines of force of the permanent magnetic field of the Earth. The direction of the rays and streamers is determined by the position of the divergence-point of an auroral crown. As a rule, the radiation-point nearly coincides with the magnetic zenith, that is, the point where the magnetic lines of force for the locality intersect the celestial sphere. In individual cases, the radiation-point may be situated several degrees from the magnetic zenith but, until recently, its average position was considered to be that of the magnetic zenith [compare 796]. These conclusions were based on visual observations, which are subject to considerable uncertainty, and therefore small average deviations from the magnetic zenith were considered to be due to errors.

A more accurate determination can be obtained from photographs of crowns. In this way Vegard and Krogness [851] determined the radiation-point from photographs of auroral crowns obtained at the Haldde Observatory (northern Norway) in 1914. At the same time, Vegard also treated a series of earlier observations to determine height, *h*, and azimuth, *a*. The results are summarized in Table 1.

TABLE 1.—*Heights and azimuths of aurorae from earlier observations*

Station	Radiation-point		Magnetic zenith		Number observations
	h	*a*	*h*	*a*	
	°	°	°	°	
Bossekop, 1839–40	76.1	− 7.73	76.3	−10.8	43
Jan Mayen, 1882	78.1	−36.2	79.0	−29.9	29
Kingua Fjord, 1882	83.3	−70.4	83.5	−73.5	6
Nain, 1882	79.6	−36.6	80.0	−44.0	38
Cap Thordson, 1882	79.9	− 7.2	80.6	−12.7	11
Bay Treurenberg, 1899–1902	80.8	− 8.2	81.3	−10.6	36
Haldde, 1914 (Vegard and Krogness)	75.4	− 2.7	76.7	− 2.5	11
Oslo, 1917–21 (Störmer)	70.0	− 9.8	70.8	− 9.7	9

We notice the remarkable fact that for all stations the radiation-point is situated, on an average, below the magnetic zenith. It was found [845, 851] that the angular distances between the radiation-point and magnetic zenith are far too large to be explained by the curvature of the magnetic lines of force.

From a study of the structure and luminosity-distribution along the auroral streamers, Vegard concluded that the ray-streamers should always mark the direction of the lines of force of the magnetic field, as it actually exists at the moment and in the region of the auroral display considered. In other words, the radiation-point should always give the instantaneous position of the magnetic zenith in the auroral region. Consequently, the deviation of the radiation-point should be due to changes of the magnetic field accompanying the auroral display, which is mostly due to extra-terrestrial current-systems. These systems, on an average, will have the effect of producing a lowering of the magnetic zenith or of increasing the curvature of the magnetic lines of force. The results obtained by Vegard and Krogness were confirmed by Störmer [835] from studies of photographs of crowns obtained at Olso. His results are given in the last line of Table 1.

The deviations of the radiation-point from the undisturbed magnetic zenith measured on the surface of the Earth are illustrated in Figure 1. The encircled numbers correspond to the numbers of Table 1. Numbers 1 to 6, corresponding to visual observations, are less reliable and show considerable deviations not only in height but also in azimuth. Numbers 7 and 8 correspond to measurements from auroral photographs; in these cases the deviation from the magnetic meridian is certainly smaller than the possible error, while the lowering of the radiation-point is considerable.

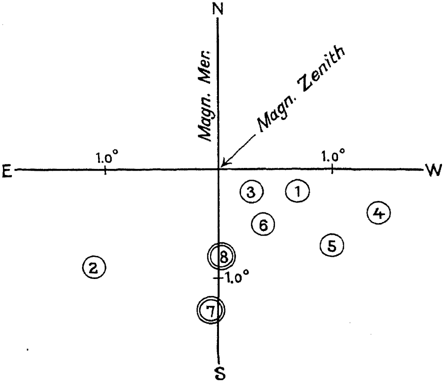


FIG. 1.—Deviations of radiation-points from undisturbed magnetic zenith measured on Earth's surface.

(3) DIRECTION OF ARCS AND BANDS

Arcs, bands, and draperies have a tendency to extend along some horizontal direction, which is typical for the locality and may be somewhat different for the various forms. The preferred direction is usually not perpendicular to the astronomical or the magnetic meridian.

The first systematic study [845, 851] of the directions of arcs, bands, and draperies was made from auroral photographs taken at the Haldde Observatory and from data at a number of polar stations during the First Polar Year of 1882–83. The results from the material at Haldde are the more accurate because they are based on parallactic photographs taken simultaneously from two stations according to the method of Störmer [832].

The horizontal projection of an arc can be approximately represented by a straight line for which one direction is not distinguished from the other. A general theory of such line-complexes with regard to distribution of direction was developed by Vegard [851]. He defined the average "vector," D, as follows: When all lines have the same direction, $D = D_{\text{max}} = 1$; when the directions of the lines are arbitrarily distributed, $D = D_{\text{max}} = 2/\pi = 0.635$. The quantity

$$G = (D - D_0)/(D_{\text{max}} - D_0) = (D - 0.635)/0.365 \qquad (1)$$

gives a measure of degree in which the lines concentrate round a certain direction. For lines having perfectly arbitrary distribution, $G = 0$; when all lines have the same direction, $G = 1$. From the point of view of the auroral theory, the direction of bands should be seen in relation to the plane passing through the magnetic axis of the Earth or to the magnetic meridian passing through the magnetic axis-point, which according to Carlheim-Gyllensköld [1263] has the following coordinates: north latitude, $\varphi = 78^\circ\,54'$; west longitude, $\lambda = 59\overset{\circ}{.}056 + 0\overset{\circ}{.}117805 \times T$, where T is the number of tropical years from 1900.

Let A_m be the azimuth of the magnetic meridian referred to the magnetic axis-point and let a be the azimuth of the average vector. Then the *magnetic azimuth*, a_m, of the average vector will be $a_m = a - A_m$. Many parallactic photographs at the Haldde Observatory during 1914 [851] gave the results of Table 2.

TABLE 2.—*Auroral elements at Haldde Observatory*, 1914

Form	a	a_m	D	G
	° ′	° ′		
Split pulsating arcs	63 35	92 03	0.976	0.933
Diffuse arcs	73 10	101 38	0.964	0.900
Drapery-shaped arcs	71 15	99 43	0.908	0.747
Draperies	104 15	132 43	0.795	0.439

The directions of split pulsating arcs show the smallest scattering (largest value of G). The directions of draperies are much scattered and the average azimuth is much larger than for the other band-forms. For the diffuse bands, the diagram indicates two pronounced directions, one nearly coinciding with the direction of the average vector, D, and another with a magnetic azimuth, $a_m = 118\overset{\circ}{.}7$.

Vegard further determined the average direction for a number of other polar stations for which the directions of band-forms were fairly definitely stated. The results are sumarized by Table 3.

TABLE 3.—*Average auroral directions*

Station	Latitude	Longitude	A_m	a	a_m
	° ′	° ′	°	°	°
Haldde, 1914	69 56	22 55 E	−28.46	72.7	101.1
Bossekop, 1839	69 56	22 55 E	−30.53	69.4	99.9
Cap Thordsen, 1882	78 29	15 42 E	−48.62	62.6	101.2
Jan Mayen, 1882	71	8 28 W	−36.1	63.3	99.4
Godthaab, 1882	64 11	51 44 W	−12.2	47.9	60.1
Nain, 1882	56 33	61 40 W	− 3.55	98.4	101.9
Kingua Fjord, 1882	66 36	67 22 W	− 1.24	66.3	67.5
Fort Rae, 1882	62 39	115 44 W	+22.83	128.9	106.1
Point Barrow, 1882	71 23	156 40 W	+32.62	133.8	101.7
Ssagastyr, 1882	73 23	126 36 E	+ 6.3	84.3	78.0
Fort Conger, 1882	81 44	64 45 W	Irregular distribution		
Bay Treurenberg, 1900	79 55	16 52 E	−49.52	75.9	126.4
Gjöahavn, 1903–05	68 37	95 45 W	+22.0	135.0	113.0
King Point, 1905–06	69 07	138 08 W	+32.0	132.0	100.0

We notice that most stations give an average direction of bands with a magnetic azimuth somewhat greater than 90°. The few exceptions may be due to the unsatisfactory way in which the directions were indicated.

The westward-directed end of a band is thus not quite perpendicular to the magnetic meridian referred to the axis-point but is directed somewhat to the north of this direction. This fact is of considerable importance in connection with the auroral theory and the question regarding the sign of the charge carried by the electric rays. It is also of interest to notice that for the station Fort Conger, situated close to the magnetic axis-point, the bands are perfectly irregular as regards direction. The absolute magnitude of D was found to be 0.63. This means an arbitrary distribution, that is, $G = 0$. For Gjöahavn and King Point, however, situated near the ordinary magnetic pole, we find very definite directions with a normal average magnetic azimuth of 113° and 100° for the two stations, respectively. This result shows that we are right in referring the direction of bands to the magnetic axis-point.

(4) GEOGRAPHICAL DISTRIBUTION OF AURORAL FREQUENCY

E. Loomis [1324] was the first to notice the main feature with respect to the geographical distribution of auroral frequency. He found that passing from lower latitudes the frequency first increased to a maximum, after which it showed a marked decrease. Some years later H. Fritz [812] published his well-known map giving curves of equal frequency and the curve of maximum frequency, usually called the auroral zone. These curves were approximately circles *with their common center coinciding with the magnetic axis-point.* The material on which the map of Fritz is based is no doubt very unsatisfactory and incomplete, and the geographical distribution of frequencies, which is so fundamental for the auroral theory, should be redetermined on the basis of more extensive material and by more refined methods. By such a redetermination we ought to direct our attention to the cases where the aurorae have appeared near the zenith. In other words, an aurora should be counted only for that locality where it has appeared near the zenith. Counted thus, the maximum of frequency no doubt would be more pronounced than it appears from the map of Fritz, or the frequency would diminish more rapidly when we pass from the auroral zone either toward the south or in the opposite direction. Revision of the map of auroral frequency will be an important task for future auroral investigators.

(5) DIURNAL DISTRIBUTION OF AURORAL FREQUENCY

The observations which up to the present form the basis of our determination of auroral frequency consist in visual observations (or perhaps ordinary photographs) of an auroral display, and therefore are restricted to the night hours. But apart from this restriction it is difficult to get a quantitative measure of what we might call the quantity of auroral luminescence. Usually the following procedure is adopted: The time of the day is divided into equal intervals—say half an hour—and for a certain period considered we count the number of times aurorae have appeared in each such interval. This method has the disadvantage that strong and weak aurorae count equally, and further the method gives an upper limit of frequency which at the auroral zone may be nearly reached for all hours of the night. The method is likely to give a fairly true picture at lower latitudes, or when we restrict our attention to certain auroral types, or in all cases when we count phenomena of fairly small frequency. Angot gives, for lower latitudes in Europe and Canada, a maximum occurring between 9 and 10 o'clock in the evening.

Investigations on the diurnal variation near the auroral zone, including special types, have been undertaken by Pallander, Wijkander ["Kgl. Vet. Handb." **14,** No. 15, 1876], Tromholt [1355], Carlheim-Gyllensköld [803], and A. Paulsen [827, 828]. Some of the main results are: (*a*) Most types show a maximum in the evening and one in the morning; (*b*) the strong, rapidly moving aurorae are more frequent in the evening, while weak, quiet forms are most frequent in the morning.

In order to obtain a more objective and reliable method for the study of the auroral variations, Vegard [1359] proposed registering the total luminosity by means of a photoelectric cell. Auroral intensity-curves so obtained might then be of great value for the study of the connection between aurorae and magnetic disturbances. Observations of this kind were made at the Auroral Observatory at Tromsö by L. Harang and K. Kreielsheimer.

L. Harang [1319] adopted a spectrographic method to record the average intensity of the green auroral line for each hourly interval. His method has the advantage that it makes possible recording of auroral intensity during hours of moderate daylight.

To obtain a fairly correct impression regarding the diurnal variation, taking into account the intensity, we can utilize the fact that very intense aurorae are usually in rapid motion. From this point of view, Vegard [1357] discussed the auroral observations from a number of stations occupied during the Polar Year of 1882–83; he discussed only draperies, rays, and crowns. He found a pronounced evening maximum and an indication of a weaker one in the morning. The results as regards the evening maxima are given in Table 4.

TABLE 4.—*Times of evening auroral maximum*

Station	Latitude	Longitude	Local time	
			Astronomic	Magnetic
	° ′	° ′	*h*	*h*
Bossekop	69 57	23 15 E	9.25 P.M.	11.0 P.M.
Cap Thordsen	78 28	15 42 E	8.0 P.M.	11.0 P.M.
Godthaab	64 11	51 43 W	9.8 P.M.	10.5 P.M.
Kingua Fjord	66 36	67 15 W	10.6 P.M.	10.7 P.M.
Fort Rae	62 39	115 44 W	12.0 P.M.	10.7 P.M.

It is to be noted that the principal maximum occurs at quite different local times from 8^h to 12^h. Vegard calculates what he calls "magnetic local time," referred to the magnetic axis-point as pole. From the values in Table 4 we see that within *the limit of error the principal maximum occurs at the same magnetic local time, about one hour before magnetic midnight.*

The aurorae also show marked diurnal variations with regard to geographical position, direction of motion, and direction of bands. The change of geographical position may be roughly characterized in the following way: At a place to the south of the auroral zone in the Northern Hemisphere the aurorae early in the evening appear from the north and draw more or less gradually toward the south, reaching their most southerly position during the hours of highest intensity. After midnight the aurorae draw northward again. There thus seems to be an intimate correlation between intensity and position, in such a way that *an increase of intensity is accompanied with a motion toward lower latitudes.*

From the material collected at Cap Thordsen, Spitzbergen (1882–83), and from Bravais' observations at Bossekop (1838–40), Carlheim Gyllensköld found a pronounced diurnal variation of the direction of arcs. Table 5 gives the average azimuths—astronomical a, magnetic a_m—for the westward-directed end, corresponding to arcs appearing before and after midnight.

TABLE 5.—*Azimuths of auroral arcs*

Time of day	Bossekop (1838–40)		Cap Thordsen (1882–83)	
	a	a_m	a	a_m
	°	°	°	°
Before midnight	72.1	102.6	67.9	116.5
After midnight	65.4	95.9	47.4	96.0

(6) CORRELATION BETWEEN AURORAE AND SOLAR ACTIVITY

That the aurorae tend to occur at the time when sunspot-groups pass near the central meridian of the Sun was already noticed by Mairan [1329] about the middle of the eighteenth century. It was shown by Warren de la Rue, Carrington, Seccie, Spörrer, and R. Wolf that the auroral frequency followed the 11-year sunspot-cycle. The 11-year period seems to be more pronounced at lower latitudes than near the zone of maximum auroral frequency.

From extensive observational material collected by Rudolph and later by Kleinschmidt in Greenland, Tromholt found that the aurorae appear near the auroral zone almost as frequently at sunspot-minimum as at sunspot-maximum. This result may be partly due to the fact that the frequency is determined without regard to intensity, but still the fact remains that the 11-year period becomes more pronounced when we pass away from the auroral zone. Vegard [844, 848] accounted for this by assuming that the aurorae are carried toward lower latitudes through the effect of magnetic disturbances; for it is well known that the magnetic disturbances are closely related to sunspots and show a pronounced 11-year period.

We meet with a very similar case when we consider the annual variation of auroral frequency. At lower latitudes we find two maxima coinciding with the equinoxes. When we pass toward the auroral zone the two maxima approach each other, and near the auroral zone we have one maximum in midwinter. According to Vegard [844], this difference in the annual variation is to be explained as an effect of magnetic disturbances. The magnetic storminess has two pronounced maxima at the equinoxes, and these maxima—as shown by Birkeland [66]—are not restricted to lower latitudes but are very pronounced for polar magnetic storms with their centers near the auroral zone.

The annual period is partly an effect of the annual period of the magnetic disturbances, which in turn is explained by the variation of the position of the Earth relative to the two zones on the Sun where most sunspots appear.

The aurorae have a tendency to occur 27 days after a strong auroral display—the same is found for magnetic disturbances. This "monthly period" is due to the fact that an "active area" on the Sun can remain active during several revolutions. After some revolutions, new active areas set in and take the lead, and there is a change of phase in "monthly period." Therefore, if we take the average for a very long period, the amplitude of the monthly period will vanish.

(7) POSITION IN SPACE OF THE AURORAE

The position in space of the aurorae was determined more than 200 years ago by Mairan. The method used was to measure height and azimuth of certain characteristic outlines of an auroral form simultaneously from two stations. As there was no communication by telegraph or telephone in those days, these early measurements were most uncertain and could be successfully applied only to somewhat quiet aurorae with fairly sharp boundaries, such as arcs. Measurements of this type, undertaken at lower latitudes by Dalton, Potter, Cavendish, Airy, and Fearnley, placed the aurorae at altitudes between about 80 and 160 km. Others like Wrede and Loomis found that aurorae might extend as high as 1,000 km.

In the polar region the auroral altitudes were measured by Bravais and Lottin at Bossekop (1838–39). They found altitudes varying between 100 and 200 km—in good agreement with more exact measurements of recent years. They did not accept the common belief that aurorae may appear close to the ground but explained this as an optical illusion. Later on, a number of observers, like Lemström, Weyprecht, and A. Paulsen, stated that they had observed aurorae in the polar regions only a few hundred meters above the ground. These statements have not been confirmed by later, more reliable measurements.

To determine fairly exactly the position in space of irregular forms and rapid motions of the aurorae, we must fix the instantaneous outlines of the same part of an aurora simultaneously from two stations. For somewhat quiet forms, a method was adopted by which the outlines were drawn on star-maps in rapid succession, giving the times for each drawing. From such series at two stations, simultaneous outlines could be found by interpolation. Such a procedure can still be used with advantage when no better arrangements can be made.

If, however, we were able to fix the auroral form by a photograph of short exposure and the two stations could operate simultaneously, we should have a reliable method for measurements of height. If the stars appear on the picture, we should be able to determine the altitude of any point from the displacement of the two pictures relative to the stars, just as in the case where outlines were drawn on star-maps. Through the telephone and through the development of the photographic technique, such an ideal method has now become possible.

The first attempts to take auroral photographs were made by Brendel [1310], and with the cameras and plates available at that time even very strong aurorae required exposures of seven sec or more. During 1899–1900, auroral photographs were taken by Sykora [1354] and by Westmann [852]. Improvements rapidly followed, increasing sensitiveness of the photographic film and light-power of lenses. In 1910 Störmer, using a cinema lens, obtained photographs of strong aurorae with an exposure of only one-half sec, making it possible to take fairly distinct photographs even of fairly rapidly changing aurorae. On the basis of such work, Störmer [832] developed his simple and practical photographic method for the determination of auroral altitudes. His first measurements, which were undertaken at Bossekop in 1910 with a short base-line (distance between two stations) of 4.5 km, gave altitudes between 40 and 370 km. Owing to the short base-line, the low value of 40 km was most uncertain. Graphical and mechanical devices have been developed by Störmer, Vegard, and Harang to simplify the laborious calculations. A suitable camera, which makes it possible to take six photographs on each plate, was constructed by Krogness and is now commonly used.

Since 1910, photographic measurements of height have been made by a number of investigators. In 1912, measurements were undertaken by Krogness and Vegard with a base-line extending from Haldde to Bossekop (12.5 km), and by K. Wegener at Spitzbergen (base-line ten km). Krogness and Vegard found the lower limit between 81 and 137 km. Wegener found heights varying between 70 and 200 km. During 1913–14 many photographs were obtained at the Haldde Observatory under the direction of Krogness with either Bossekop or Gargia as the second station. This extensive material was compiled by Vegard [851, 1382].

In 1913 Störmer observed again at Bossekop, but with a longer base-line of 27.5 km. During recent years, Störmer made most important measurements at lower latitudes at Oslo, Kongsberg, Aas, and Dombås. An extensive series of parallactic photographs was obtained, from 1929, at the Auroral Observatory at Tromsö by Harang and Tönsberg, and some of the results were recently published [816]. Extensive and no doubt important material was also obtained during the Second Polar Year of 1932–33 at various localities.

A more systematic study of the lower and higher limit of the various auroral types was undertaken by Vegard and Krogness [851]. They gave curves and tables showing the relative probability for a certain auroral form to appear with its lower or upper limit at a certain altitude and determined the average altitudes. Similar tables and curves were published by Störmer for Bossekop and for stations near Oslo and by Harang and Tönsberg for the Auroral Observatory at Tromsö.

(8) The lower limit

Table 6 summarizes the average values of the lower limit for various auroral forms as derived from the results of various investigators.

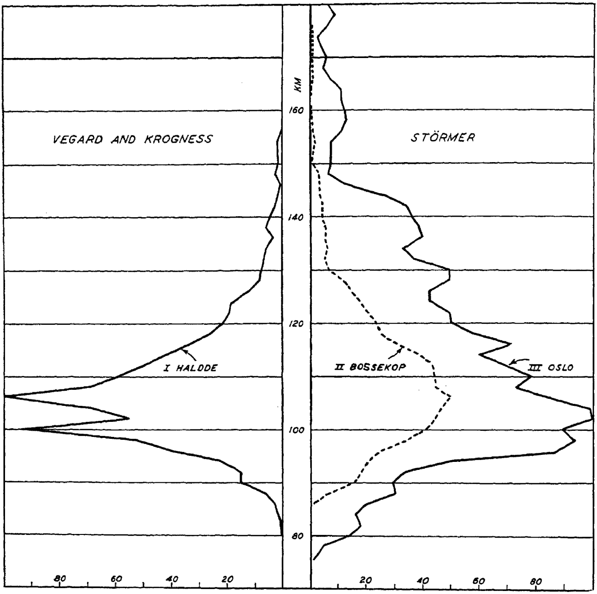


FIG. 2.—Total distribution all forms, of lower limits for auroral heights.

The quiet forms, diffuse arcs, split bands, and pulsating areas give smaller average lower limits than the forms with pronounced radiant structure. The difference is especially marked in the case of typical rays. This result, which was first found by Vegard and Krogness, has been confirmed by Störmer, Harang, and Tönsberg, both for the polar region and at lower latitudes. Comparing the results for localities near the auroral zone with those at lower latitudes (Oslo), we notice that the average height of the lower limit for the quiet forms and draperies is very nearly independent of latitude, although, as we shall see, some differences may be found in the distribution-curves. This is a very important result in relation to the auroral theory. However, for the ray-form, *the average altitude of the lower limit increases as we pass from the auroral zone toward lower latitudes.* This difference with regard to rays is even more pronounced when we regard the upper limit.

TABLE 6.—*Lower limits of auroral displays*

Auroral type	Observatory and authority							
	Haldde—Vegard-Krogness		Bossekop—Störmer		Tromsö—Harang-Tönsberg		Oslo—Störmer	
	Height, km	No. observations	Height, km	No. observations	Height, km	No. observations	Height, km	No. observations
Rays	113.2	61	128.9	19	117.0	127	146.9	119
Draperies	109.8	409	108.1	506	112.9	1,039	100.0	150
Drapery-shaped arcs	106.6	888			106.7	1,175		
Diffuse arcs	109.1	409	111.8	415			118.5	201
Pulsating areas	106.0	160	.....	....	107.3	66		

The distribution of the lower limits for the various heights is represented in Figure 2. The curves give the "total" distribution of all forms taken together. Comparing the curves for Oslo with those for Haldde and Bossekop, we notice that the range of the altitudes increases as we pass from the auroral zone toward lower latitudes, while the height of *maximum frequency shows a slight decrease.*

(9) THE UPPER LIMIT

Average values and height-distribution of the upper limits of various types near the auroral zone were given by Vegard and Krogness [851], and these are summarized by Table 7.

TABLE 7.—*Upper limit of aurorae observed at the Haldde Observatory*

Type	Rays	Draperies	Drapery-shaped arcs	Diffuse arcs
No. observations	43	215	174	57
Height	250 km	176.3 km	174.4 km	143.4 km
Average vertical extension (length of streamers)	137 km	67 km	68 km	34 km

The last line of Table 7 gives the difference between the average upper and lower limits, representing the average vertical extension of the streamers. The height of the upper limits is much greater for rays than for the other forms, and the average length of streamers is very much greater. The average length of the streamers for draperies and for drapery-shaped arcs is almost the same.

The upper limit of rays is very much greater at lower latitudes. The highest upper limit of rays found by Krogness and Vegard at Haldde is 335 km, the greatest height observed by Störmer at Bossekop is 323 km, and the greatest height measured by Harang and Tönsberg is 170 km. At the stations near Oslo, Störmer has recorded auroral rays reaching as high as 750 to 800 km. His results [835] show three rays higher than 700 km, six rays between 600 and 700 km, 16 rays between 500 and 600 km, and 37 rays between 400 and 500 km. *Thus the maximum height reached by an auroral ray increases rapidly when we pass from the auroral zone toward lower latitudes.*

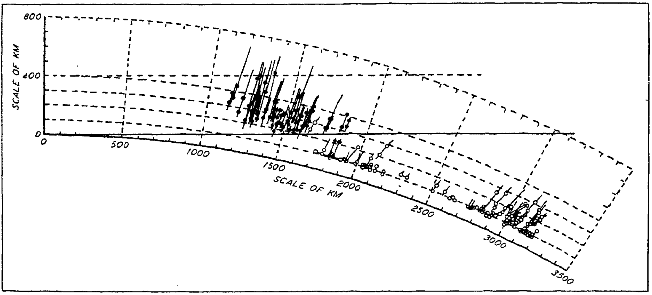


FIG. 3.—Observations sunlit auroral rays, March 15–16, 1929 (*after Störmer*).

These facts were accounted for by Vegard through his investigations on the auroral spectrum and the state of the upper atmosphere, which will be dealt with in a later section. According to him, this effect of latitudes is closely related to the fact that, according to Störmer's measurements, the rays appearing early in the evening—when the auroral region is still in the Sun—extend much higher than rays later in the night. Störmer's remarkable observations of sunlit auroral rays during the night from March 15–16, 1929, are illustrated in Figure 3, which is taken from his paper [836].

Another most interesting case is that of auroral curtains observed by Störmer at Oslo on the evening of September 8, 1926. These curtains had a gray-violet color and appeared to have an unusually great height. The lower limit of the streamers varied between 200 and 400 km, and the upper limit could be traced to about 1,000 to 1,100 km.

An interesting case of an auroral arc with a red lower border was measured at the Auroral Observatory at Tromsö in 1932 by Harang and Bauer [815]. They found the arc descended to an altitude of 65 to 70 km. *This is the lowest height as yet measured by the photographic method.*

(10) DISTRIBUTION OF LIGHT-INTENSITY ALONG AURORAL STREAMERS

The study of the distribution of light-intensity along streamers has important bearing on the properties of those rays coming from space which produce the auroral luminescence. Vegard [845, 851, 1357] undertook the first systematic investigation of the intensity-distribution using data from parallactic photographs obtained at the Haldde Observatory by Krogness [851]. The ideal method would be to determine the distribution of luminescence by the well-known photographic-photometric method. Such a procedure is most laborious and could not be applied to the photographic material mentioned because no intensity-scale was photographed on the plates. Usually the intensity-distribution is most variable and an exact determination of the intensity-curve is of minor importance for most purposes.

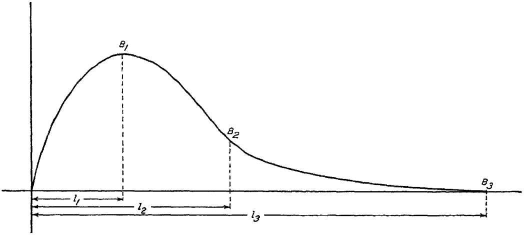


FIG. 4.—Diagram defining quantities, l_1, l_2, and l_3.

Vegard characterized the intensity-distribution by three quantities, l_1, l_2, and l_3, the meaning of which will be seen from Figure 4. l_1 is the distance from the bottom edge to the point of maximum intensity, l_2 is the corresponding distance to the point where the luminosity becomes quite faint and where the intensity-curve has a point of inflection, and 1_3 is the whole range of the luminescence. Some main features of the results appear from Table 8, which summarizes, for a number of typical auroral forms, the limits within which the quantities, l_1, l_2, and l_3, vary and their average values. The different auroral forms differ very considerably as regards intensity-distribution. Arcs and drapery-shaped arcs give almost equal, and very small, values for l_1 and l_2; for these forms most luminescence is restricted to an interval of about 14 km.

For arcs we cannot distinguish between l_2 and l_3—the luminescence practically stops at the point B_2 of Figure 4. When the radiant structure becomes very marked (draperies and rays), the quantities, l_1, l_2, and l_3, increase. For rays, the luminescence keeps a fairly constant intensity until it fades away upward—therefore only l_3 was measured.

TABLE 8.—*Auroral intensity-distribution*

Intensity	Arcs		Drapery-shaped arcs		Draperies		Rays	
	Limits, km	Average, km	Limits, km	Average, km	Limits, km	Average, km	Limits, km	Average, km
l_1	5–9	6.4	2– 11	5.8	5– 13	9.1		
l_2	10–19	14.0	5– 25	13.6	9– 21	16.3		
l_3	.....	14.0	10–125	46.7	35–115	63.4	113–250	137

A point of great interest is the smallest cross-sections which the ray-streamers may have. Vegard found that certain rays are so thin that the cross-section is only 300 to 400 meters. The distribution of light-intensity, its great variability, and the small minimum cross-section of the streamers are facts of far-reaching importance, which—as we shall see—give valuable information regarding the properties of the rays producing the aurorae.

III. THEORY OF THE AURORAE

(1) SOME GENERAL CONSIDERATIONS

It is a well-established fact that the appearance of aurorae is closely connected with the appearance of magnetic disturbances. Any theory of the aurora must account for this close relationship, and, in any case, it must contain essential features of a theory of certain types of magnetic disturbances and phenomena. Further, the auroral theory must account for all those facts and relationships which are briefly summarized in the preceding Section II. Because of the nature of the phenomenon, it will probably be impossible for any theory to be carried far enough to explain all details quantitatively, but what we can claim is that the theory is not in conflict with established facts and that it can explain the essential features in a way which may be regarded as satisfactory from sound physical reasoning.

The auroral theories are numerous and in their historical sequence they give an interesting picture of the development of natural science. Almost any important advance in physics has influenced the auroral theories, but it is evident that all of them were incomplete and unsatisfactory until physical science had discovered and studied those phenomena and processes which are instrumental in producing the auroral displays.

At present we know that rays, constituted of electrified particles, form one of the essential instruments of which any auroral theory must take account, and the discovery of the electric rays was essential for the development of a satisfactory theory. Therefore, we shall limit our description and discussions to those theories which assume the auroral luminescence to be caused primarily by electric rays of some sort penetrating into the higher strata of the atmosphere. Another fact upon which to base auroral theories is that the energy necessary for producing the aurorae and magnetic disturbances comes primarily from the Sun. Therefore, the electric rays which form the aurorae must be related, in some way or other, to solar processes. Even with these starting points, there is room for a variety of theories which differ as to the way in which solar energy is made available for the production of the electric rays and as to the composition and properties of these rays.

(2) THEORIES BASED ON THE ASSUMPTION THAT THE ELECTRIC RAYS ARE PRODUCED IN THE EARTH'S ATMOSPHERE BY SOLAR RADIATION

In 1893, Adam Paulsen [827 and 828] proposed a theory according to which the aurorae were produced by cathode rays formed in the higher strata of the Earth's atmosphere through the effect of solar radiation. This hypothesis was criticized by Birkeland, who found it not sufficient to account for essential features regarding the form and appearance of auroral and magnetic storms. A non-electric solar radiation, for example, the ordinary light-radiation, travels in straight lines and falls on the dayside of the Earth. The source of electric rays is spread over half the hemisphere and is in the immediate vicinity of the Earth. Even when we take into account the influence of the magnetic and electric fields of the Earth, such a source cannot possibly produce the very limited auroral forms like thin arcs, draperies, and rays. The precipitation of electric rays in the polar regions should fall mainly on the dayside, from which it would follow that aurorae and magnetic disturbances should have a pronounced maximum in the middle of the day, while in fact these phenomena show pronounced maxima near magnetic midnight.

A source so near the surface of the Earth cannot explain that the geographical distribution, the diurnal distribution, and the direction of bands are determined by the magnetic axis of the Earth. To explain the distribution of the aurorae round the magnetic axis-point and not round the magnetic pole, and the maximum near magnetic midnight, we must assume *that the electric rays producing the aurorae and polar magnetic storms exist as such, at distances which are large as compared with the dimensions of the Earth.*

If the electric rays were produced in the Earth's atmosphere by photoelectric effect of solar radiation, we should expect to have auroral and magnetic disturbances throughout nearly the whole time taken for an active area on the Sun to pass across the Sun's disk. In fact, aurorae and magnetic disturbances usually appear only with large intensity a few nights near the time when the active area, usually associated with a sunspot-group, passes the central meridian of the Sun. It does not help to assume fluctuations in the source, for there is no reason why the effectiveness of the source should have a maximum just when it passes the central meridian. These statements will be sufficient to show the impossibility of the auroral theory of Paulsen.

In 1906, the same hypothesis was advocated by Villard [1384] with the modification that the electric rays originated from cirrus clouds. This hypothesis was introduced to explain the narrow auroral streamers and bands, but all other arguments against the hypothesis of Paulsen still hold; furthermore, Villard's modification cannot be accepted, because the passage of the electric rays from the cirrus layer would require a much higher order of penetrating power than found from the measurements of height of aurorae.

In recent years the hypothesis of Paulsen has been taken up by Maris and Hulburt [406, 419]. Their papers contain many points of interest for the question regarding the influence of sunlight on the state of the upper atmosphere; but as their theory of aurorae and magnetic disturbances is based on the hypothesis of Paulsen, it cannot be accepted for the reasons already given. Recently, their papers have been criticized by S. Chapman [804], who sums up a number of the most important arguments against their theory.

(3) BIRKELAND'S THEORY OF AURORAE AND THE MAGNETIC DISTURBANCES

An auroral display which appeared February 4, 1872, seemed to follow the motion of the Sun; to explain this Donati suggested that currents of electricity were sent out from the Sun. In connection with experiments on cathode rays, Goldstein suggested that such rays might possibly be emitted from the Sun and would produce the aurorae and the magnetic disturbances. This suggestion did not attract much attention, and in 1896 Birkeland [1312] made certain experiments on the influence of magnetic fields on the cathode-ray streamers; these led him to the development of a new theory of aurorae and magnetic storms, based on a hypothesis similar to that suggested by Goldstein. Birkeland pursued the idea with great energy and skill. From 1896 to his death, most of his remarkable scientific activity was devoted to studies which had a bearing on the development and verification of the new theory of aurorae, magnetic disturbances, and related phenomena.

The basis of his theory is the fundamental assumption that, in addition to ordinary light, the Sun emits fairly limited bundles of electric rays.

When such a bundle comes within the neighborhood of the Earth, some of the rays may strike the upper atmosphere and produce luminescence in the form of aurorae, and the moving electric particles will produce magnetic effects which Birkeland regarded as the primary cause of magnetic disturbances. Simple considerations led him to conclude that the deviating force produced by the magnetic field of the Earth would prevent the rays from coming near the Earth in the equatorial region but would make it possible for them to strike the Earth in the polar regions.

He associated with the sunspots the source on the Sun. Thus he accounted for the close connection between aurorae and magnetic disturbances and the close correlation between these two phenomena and the sunspot-activity. In other words, his theory explains the 11-year period, the annual period, and the tendency of aurorae and magnetic storms to reappear after a period of about 27 days. Birkeland's assumption that the bundles of electric rays were associated with the sunspots was confirmed in a very direct way by some important investigations of Maunder [421], who in 1904 showed that a close correlation existed between strong magnetic storms and the appearance of sunspot-groups near the central meridian of the Sun.

To test his hypothesis and develop a well-founded theory of aurorae and magnetic disturbances, Birkeland made experiments of like kind to those which originally led him to his hypothesis. He tried to reproduce in the laboratory conditions of experiment similar to those existing in cosmic space. He constructed vacuum-discharge chambers with a volume which, in his last experiments, amounted to nearly one cubic meter. In the center of the tube was placed a sphere with a core of iron, surrounded by a magnetizing coil. This sphere, in various states of magnetization, could be exposed to cathode rays of different velocities. The precipitations were made visible by painting the sphere with a phosphorescent substance. The path of the rays was studied by phosphorescent screens suitably placed.

In this way, Birkeland showed that when the magnetization was increased above a certain limit, depending on the velocity of the cathode rays, the latter could strike the magnetized sphere—"Terrella"—only in a zone round the magnetic axis. In certain experiments, precipitations on the "Terrella" had the forms of separate patches; in other cases he got a precipitation in the form of a well-defined spiral round the magnetic axis-point. These spiral-shaped precipitations, which are to be regarded as the experimental reproduction of the auroral zone, are shown in Figure 5, which is taken from Birkeland's work [66].

Thus the zone of maximum auroral frequency appeared to be a direct and simple consequence of his basic hypothesis. He also showed that bundles of cathode rays might turn round the "Terrella"—even several times—before striking its surface in the "auroral zone." In this way we can understand that aurorae and magnetic disturbances may have a pronounced maximum near magnetic midnight. The precipitations of cathode rays on the "Terrella" have the form of narrow bands and patches similar to arcs, draperies, rays, and the other forms of luminous areas which may be observed during auroral displays. Thus simply and directly, the theory of Birkeland qualitatively explained all essential properties of the aurorae.

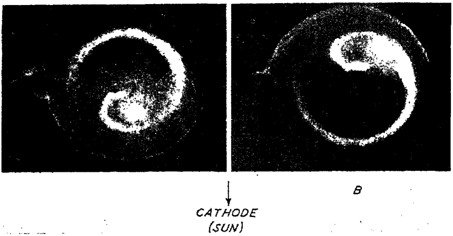


FIG. 5.—Experimental reproduction of spiral-shaped precipitations of auroral zone (*after Birkeland*)

(4) REMARKS REGARDING BIRKELAND'S WORK ON MAGNETIC DISTURBANCES

As already mentioned, the theory of Birkeland was not limited to the aurorae but he assumed that most magnetic disturbances were primarily caused by the same bundle of electric rays from the Sun which produces the aurorae. As a consequence, the magnetic disturbances were included as a most prominent part of Birkeland's researches. He organized several expeditions to the regions near the auroral zone, mostly devoted to the study of the magnetic disturbances and earth-currents. The results are given in a number of publications and especially in his uncompleted work "The Norwegian Aurora Polaris Expedition 1902–03." The two volumes which appeared in 1908 and 1913 may still be regarded as the best and most complete analysis of magnetic disturbances yet published.

The perturbations are divided into three principal groups, namely, equatorial, cyclo-median, and polar storms. A more complete description of his results falls outside the plan of this chapter. We shall draw attention only to some results regarding polar storms, because they are very closely related to aurorae. The polar storms of moderate strength have their storm-centers (maximum intensity) near the auroral zone. The intensity drops rapidly as we pass from the auroral zone toward lower latitudes. In Scotland and northern Germany, the intensity usually drops to about five per cent of its value at the center. Simultaneous observations from stations on the opposite side of the auroral zone showed that the polar storms were caused by current-systems above the Earth which came down to distances of some hundred km from the storm-center. The rapid fall of intensity from the storm-center shows that the current-systems are localized to fairly narrow areas.

A very typical magnetic field was found for simple storms of moderate strength, and this field was accounted for by a current-system above the Earth acting as though it consisted of a vertical branch coming in from space, bending in horizontal direction along the auroral zone, and leaving the Earth along another vertical branch. More irregular storms may be regarded as composed of such systems and, in the case of very strong perturbations, the storm-centers and corresponding current-systems may move toward lower latitudes and produce there almost equally strong disturbances as those observed near the auroral zone. Thus the polar storms are found to be produced by fairly local and narrow electric current-

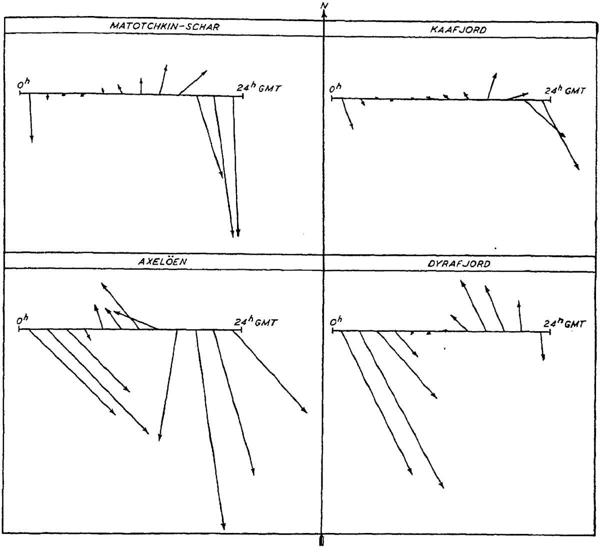


FIG. 6.—Vector-diagrams for the average polar storm.

systems, or streams of electrified particles, coming in from space, just like the aurorae and in agreement with the theory of Birkeland.

The polar magnetic disturbances appearing during the winter of 1902–03 at Birkeland's four northern stations—Kåfjord (Norway), Dyrafjord (Iceland), Axelöen (Spitzbergen), and Matotchkin Schar (Novaja Zemlya)—were treated statistically and the variation of storminess was found. The diurnal variation was determined for the positive, negative, and absolute storminess and *the average diurnal magnetic disturbance* was found. Vector-diagrams for the average storm for the four stations, corresponding to the nine months of observations, are shown in Figure 6, which is taken from Birkeland's work. The average storm has a pronounced maximum which for *all four stations appears between two and three hours after magnetic midnight.* For all four stations, especially for the three situated to the south of the auroral zone, there is a calm daytime in the forenoon at about 11 o'clock local magnetic time. *The strong maximum near magnetic midnight, seen in relation to the calm daytime near magnetic noon, shows that the polar magnetic storms are, in a most direct way, related to the Sun and that the polar storms are of fairly local nature, demonstrating that the current-systems producing them must reach a distance from the surface of the Earth and have a horizontal extension which is small compared to the diameter of the auroral zone.*

(5) STÖRMER'S MATHEMATICAL THEORY

Very early in his work, Birkeland emphasized the importance of a mathematical treatment of the problems involved in his theory of aurorae and magnetic disturbances. In his work "Recherches sur les taches du Soleil" [1313], published in 1899, Birkeland states that a mathematical theory based on his hypothesis should explain: (1) That the aurorae appear most frequently in a zone round the magnetic axis-point; (2) the formation of thin bands in the east-west direction; (3) the motion of these bands in direction north-south; and (4) the diurnal variation shown by the aurorae. All these phenomena, according to Birkeland, should be due to the deviation of the solar electric rays in the magnetic field of the Earth.

This mathematical problem involved in the Birkeland auroral theory consists first of all in the determination of the possible orbits of the solar electric rays when moving under the influence of the magnetic field of the Earth. If possible electrical fields are taken into account, the equation of motion is as expressed in equation (2).

$$m(dv/dt) = e[F + (V \times H)] \tag{2}$$

F and H are electric and magnetic forces, respectively, V is velocity, e is charge, and m is mass of the moving particle. This equation has been treated in particular cases by a large number of investigators, but Störmer has the credit of having treated it with special reference to Birkeland's theory of aurorae and magnetic disturbances.

In his first and perhaps most fundamental papers, Störmer [830, 1338] treats the problem of determining the orbits of electric rays in the field of an elementary magnet. When the solution is applied to the auroral problem, the effect of gravitation, the effect of possible electric fields of the Earth, and the mutual influence of the other electric ray-particles in the solar streams must be disregarded. Later on, Störmer extended his theory to the case where the elementary magnet is the seat of a central electric field.

From investigations on the auroral spectrum, Vegard [847] found that electric fields exist in the auroral region, but these fields may be mostly restricted to certain layers in the vicinity of the Earth and may not essentially influence the position of the precipitations of electric rays in the atmosphere, which is essentially determined by the orbits at distances large as compared with the dimensions of the Earth.

To obtain the essential features of the mathematical theory of the aurorae, we therefore do best to restrict our attention to the simple case that the rays are influenced only by the field from an elementary magnet. This is also the case most thoroughly studied by Störmer; the results [830, 833, 837, 840, 841, 1338, 1341, 1343, 1345, 1351] of his most laborious calculations are too numerous to be dealt with here. In this connection, I merely wish to call attention to some of his results as far as they can be compared with the properties of the aurorae. Brief accounts of Störmer's theory were given by Vegard [844, 848, 1364] and by Angenheister [795].

The discussion regarding the orbits which may possibly reach the Earth essentially depends on the quantity

$$\sqrt{Me/mv} = c \tag{3}$$

where c is expressed in cm, M is the magnetic moment of the Earth (8.52×10^{23} CGS units), and e, m, v are charge, mass, and velocity of the ray-corpuscle, respectively. The quantity, c, has the dimensions of a length, $(mv/e) = H\rho$, where H is the magnetic force and ρ is the radius of curvature of an orbit moving perpendicular to the magnetic lines of force. The fundamental length, c, increases as the magnetic stiffness, $H\rho$, decreases. The penetrating power necessary to account for the height of the aurorae makes it necessary to assume that $H\rho$ is so large that c comes out much smaller than the distance from the Earth to the Sun, which is the source of the radiation.

Provided c is not larger than the distance to the Sun, Störmer finds that only such orbits can reach the Earth for which the conditions of equation (4) hold.

$$-1 < \gamma < (r/2c) \tag{4}$$

γ is a parameter entering into the equations of motion, and r is the distance from the auroral region to the center of the Earth. To each value of γ within this interval there is an orbit through the origin, which as a rule passes into infinity. For suitable positions of the Sun relative to the magnetic axis of the Earth, such an orbit may be a possible path of an electric ray which leaves the Sun and reaches the Earth. A number of such orbits through the origin is shown in Figure 7, which is a photograph of one of Störmer's models. For each orbit is given the corresponding value of γ. The orbits are placed in such a way that they are supposed to start in directions which are parallel to the same magnetic meridional plane (plane through the magnetic axis). That one of these orbits may be a real orbit of an electric ray from the Sun, its direction when it passes toward infinity must form an angle with the magnetic axis which is not smaller than the smallest magnetic polar distance of the Sun—about 55°.

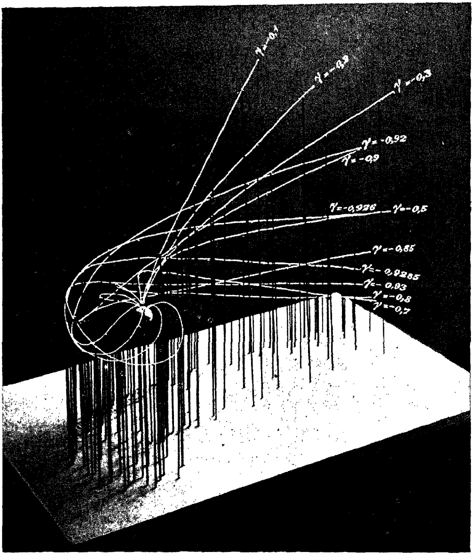


FIG. 7.—One of Störmer's models of orbits of electric rays in field of elementary magnet.

Orbits for which $|\gamma| < 0.2$ give magnetic polar distances smaller than 55° and cannot be considered in connection with the formation of aurorae.

The orbits shown in Figure 7 will strike the Earth at points which define the "curve of precipitation" for electric rays of definite properties coming from the Sun. This curve of precipitation is shown in Figure 8; it forms a spiral round the magnetic axis, just like the spirals of Figure 5 found by Birkeland from experiments with his "Terrella." The γ-values are given for a number of points along the precipitation-curve.

The fact that aurorae as well as the magnetic polar storms are mainly restricted to the nightside would give a further limitation of the interval of possible orbits. By possible orbits we mean those which have so large a probability of occurrence that they may essentially influence the geographical and diurnal distribution of aurorae and polar storms. The rays should then correspond to an interval

$$-1 < \gamma < 0.7 \tag{5}$$

The magnetic polar distances (α_γ) of the point of precipitation is approximately given by the formula

$$\alpha_\gamma = \sqrt{-2\gamma r/c} \tag{6}$$

The values of α_γ must vary within limits, which correspond to the limits found for γ or

$$\sqrt{2\gamma/c} > \sin \alpha_\gamma > \sqrt{1.4\gamma/c}$$

Thus the mathematical theory leads to the result that the magnetic polar distance of the spots of precipitation should lie within a fairly narrow limit. In other words, the existence of a zone of maximum frequency of aurorae and magnetic disturbances is a necessary consequence of the basic hypothesis of Birkeland.

Most polar storms should correspond to values of γ nearly equal to -1 and the theoretical magnetic polar distance of the auroral zone should be given by

$$\sin \alpha_0 = \sqrt{2r/c} \tag{7}$$

Störmer has calculated α_0 corresponding to various values of the magnetic stiffness, $H\rho = (mv/e)$, as shown in Table 9.

TABLE 9.—*Theoretical magnetic polar distance of auroral zone*

Type of rays	mv/e	c	α
		km	
Cathode rays	108	89×10^5	2.3
	540	40×10^5	3.4
β rays	1,800	22×10^5	4.5
	4,500	14×10^5	5.8
α rays	291,000	1.8×10^5	16.6
	398,000	1.46×10^5	18.1

The actual magnetic polar distance of the auroral zone is about 20°. If the rays producing aurorae and magnetic storms were moving in accordance with the theory of Störmer, a magnetic stiffness, (mv/e), as large as that of α rays would be required to account for the observed angular diameter of the auroral zone. The mathematical discussions of Störmer are extremely valuable in an exact foundation of the theory of aurorae. Like the experiments of Birkeland, his mathematical theory can account for essential features regarding the appearance of aurorae, but as we shall see it is incomplete when we enter into details and ask for a quantitative agreement.

Doubtless Störmer's theory gives the right orbits of an electric ray moving in the field of an elementary magnet. The correctness of Störmer's mathematical treatment of this problem has been confirmed by comparison with Birkeland's experiments and with those of Villard [1384] and Brüche [802, 1314]. Birkeland tried to reproduce the conditions existing during an auroral display and put a magnetized sphere, contained in a large vacuum-reservoir, into a stream of cathode rays, whose cross-section as a rule was large as compared with the dimensions of the "Terrella." As already mentioned, he actually reproduced the essential features of the geographical and diurnal distribution of the aurorae.

Villard and Brüche, on the other hand, worked with long and narrow pencils of rays, which maintained a small cross-section also in the magnetic field; thus they could make visible the orbits of cathode rays in a magnetic field. Apart from the beauty and physical significance of these experiments, their interest in relation to the auroral problem lies in the fact that both, but especially Brüche, were able to reproduce a number of those orbits which had been calculated by Störmer and thus further to confirm the correctness of the latter's mathematical calculations. Brüche's experiments, however, do not yet include definite orbits which pass through the origin (strike the Earth) and which are the most important for the auroral problem.

(6) THEORETICAL EXPLANATION OF THE AURORAL FORMS

Störmer's theory of the orbits through the origin, as illustrated in Figure 7, shows that for each position of the Sun there should be only one or but few definite points where narrow bundles of rays may strike the Earth and thus produce aurorae. This holds, at any rate, for the part of the precipitation-curve drawn in Figure 8 which corresponds to absolute values of γ less than 0.93. In the interval $0.93 < |\gamma| < 1$, the orbits are complicated and may pass several times around the Earth. It is possible that for a given position of the Sun a considerable number of orbits in this γ-interval may strike the Earth. Therefore, from the theory we may easily understand the formation of auroral rays and ray-bundles and luminous areas, but when we attempt to explain the formation of long arcs, bands, and draperies we meet with some difficulties.

The spiral precipitation-curve, Figure 8, is not obtained for any single position of the Sun, but we should get, as a rule, only a few widely separated spots on this curve for each position of the Sun. Störmer [1338] has shown that under certain conditions a ray-bundle from a circular source on the Sun may spread out to a thin drapery when it enters the atmosphere, but this transformation of the cross-section of a ray-bundle takes place only for definite positions of the Sun. The formation of draperies, however, may occur at any hour of the night and at any time of the year and does not seem to depend on the magnetic declination of the Sun. It might be argued that the number of solar positions which may give draperies varies very largely when we regard the orbits in the γ-interval near -1; but the orbits of this interval ought to strike the

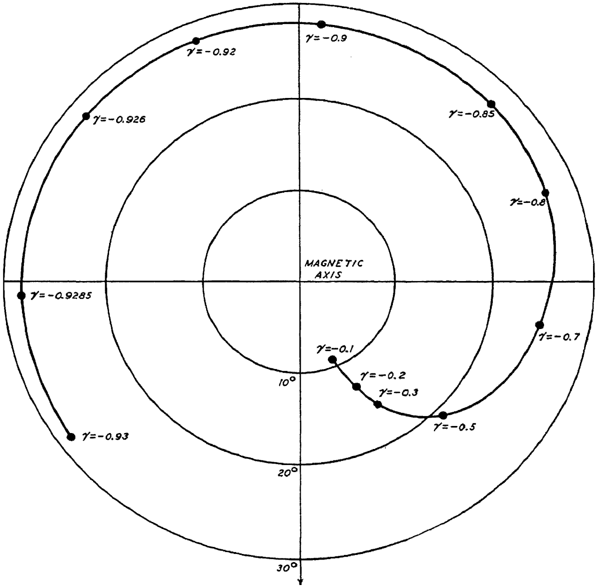


FIG. 8.—"Curve of precipitation" for electric rays of definite properties coming from Sun.

Earth as frequently on the dayside as on the nightside, contrary to observed facts. The auroral theory therefore is still incomplete, and the formation of draperies seems to be essentially influenced by certain effects which are not taken into account by the mathematical theory.

A theory of auroral curtains different from that of Störmer was proposed by Birkeland [374]. He assumed the curtains to be formed by ray-bundles added together. One bundle may have passed n times round the Earth, the next $(n + 1)$ times, and so on. However, it does not seem probable that two such ray-bundles should add up close to each other.

Vegard [844, 848, 1364] explained the formation of draperies as essentially due to the perturbing influences of the extra-terrestrial current-systems which are in operation during an auroral display. This would account for the fact that the appearance of draperies usually marks the time when the magnetic disturbances have their greatest intensity. Another possibility will be dealt with in connection with the properties of ray-bundles.

The theoretical difficulties are even greater when we apply the mathematical theory to the formation of the very long arcs. The transformation of the cross-section of a ray-bundle may account for the formation of a short and thin drapery but cannot explain the formation of an arc which may cover a large part of the auroral zone. Vegard [844, 848, 1364] holds that the formation of long arcs, like that of draperies, is essentially due to perturbing influences of extra-terrestrial current-systems.

The distance of these current-systems must be fairly small compared with the distance to the Sun, but large compared with the diameter of the Earth. The perturbing influence of such a system will have the same effect as if the current-systems themselves formed a kind of secondary source of electric radiation. An extensive source somewhat near the Earth may give a precipitation which extends over large parts of the auroral zone but, in order to explain the orientation of the arcs relative to the magnetic axis-point, it is necessary to assume that the distance of these current-systems (secondary sources) is large as compared with the dimensions of the Earth. This explanation is in good agreement with the experiments of Birkeland. For rays from a large source (a cathode of large area) he obtained a precipitation in the form of a continuous spiral. In his experiments the distance from the center of the "Terrella" to the cathode was eight times the radius of the "Terrella."

(7) MOTIONS OF THE AURORAE

On the basis of Birkeland's hypothesis and the mathematical theory of Störmer, we may easily understand the great variability and rapid motions shown by the aurorae. Changes of intensity may be due to variations in the source on the Sun and to the change of probability that the ray-bundles may strike the Earth. This change of probability may be due to the change of the magnetic declination of the Sun caused by the rotation of the Earth or by the rapid changes of the perturbing influence which the "effective ray-bundles" suffer.

These variations in the Sun's magnetic declination and the perturbing influences may also account for the rapid and irregular motions shown by rays and draperies. The arcs usually show motions and changes of a somewhat regular type which ought to have a simple theoretical explanation. During the evening the arcs usually move toward lower latitudes. An effect of this type can be explained since the curve of precipitation has the form of a spiral. If the electric rays have a negative charge, the precipitation-curve on the Northern Hemisphere would have a form like Figure 5-*A* or Figure 8; this spiral form would make the aurorae move southward during the evening. After midnight, however, the arcs move toward the north and this motion could not be due to the spiral form. As already mentioned, Vegard [844] assumes that aurorae also move toward lower latitudes by the effect of magnetic disturbances. Doubtless this effect is, as a rule, the more prominent and will more or less mask the "spiral effect."

The average direction of the arcs shows a diurnal variation [851] such that the azimuth of the end directed westward is larger in the evening than in the morning. Independent of any assumption with regard to the sign of the charge of the rays, such a diminution of the azimuth during the night is what follows from the spiral-shaped curve of precipitation. However, we must take into account the fact that the directions of arcs may vary greatly in individual cases; these variations, which are due to perturbing influences, may also influence the average direction and its diurnal variation.

IV. ELECTRIC RAYS, THEIR PROPERTIES, ORIGIN, AND CONSTITUTION IN RELATION TO THE THEORY OF AURORAE AND MAGNETIC DISTURBANCES

(1) Absorption of the solar electric rays in the atmosphere

The corpuscles forming the solar electric rays may be electrons, positrons, or electrically (usually positively) charged atoms and molecules. The solar ray-bundles may also consist of a mixture of such particles. The formation of positrons seems to be associated with elementary processes of an energy much higher than that which can be assumed for the solar rays if they are composed of particles with masses as small as those of the electrons. Further, the positrons probably disappear soon after their formation. Doubtless the number of positrons emitted from the

Sun, therefore, is negligible as compared with the number of corpuscles which form the main part of the electric ray-bundles from the Sun.

Electron rays and atomic rays differ so considerably that it might seem possible from the properties shown by the aurorae to decide which of these types of corpuscles forms the predominant part of the rays producing the aurorae. The two groups of rays have different signs of charge and for the same penetrating power the electron rays are much more easily deflected in a magnetic field.

The measurements of height of the aurorae give us a means of estimating the order of magnitude of the penetrating power of the solar electric rays. The absorption of positive rays in the atmosphere was first studied by Vegard [1357] and later by Swinne [1353] and Störmer [834, 1346]. The absorption of electron rays was studied by Lenard [1323], Störmer [1338], and Vegard [1356, 1360].

Let the partial pressure at a height, h, of the gases which constitute the atmosphere be $p_1, p_2, \ldots p_i$. Then the air-equivalent through which a positive ray has to pass when it enters the atmosphere to reach the height, h, will be

$$\gamma_h = (3.8/D_0 g)\Sigma(p_i/\sqrt{A_i}) \tag{8}$$

A_i is the atomic weight of the component, i, D_0 is the density of air at 0° and at pressure 760 mm, and g is the acceleration of gravity—approximately independent of the height. The determination of the partial pressures in the auroral region is very uncertain. Until recently it was commonly assumed that an ideal equilibrium existed above a certain height, below which there was a constant composition and perfect mixing and above which the pressure of each gas varied as though the others were not present. Calculations on such a basis, for example, by Wegener, Jeans, Chapman, Milne, and Störmer, led to the conclusion that the light gases, helium and hydrogen, dominated above, say 110 km.

Analysis of the auroral spectrum, to be dealt with later, shows that practically complete mixing exists from the ground and up to the auroral region. On the other hand, the gas in the auroral region becomes ionized and is influenced by electric fields. These electric influences violate the ordinary formula, $dp = -\rho g dh$, which determines the variation of pressure with altitude of an electrically neutral gas. The influence of the electric fields on the distribution of matter in the upper atmosphere cannot be calculated exactly but it will tend to make the density larger than in the case of a neutral gas. The influence of the electric fields on the distribution of matter will probably be small up to about 100 km; for the region below we may regard the atmosphere as perfectly mixed and having practically the same composition as near the ground (apart from the water-vapor content near the ground and some ozone higher up).

At heights below 100 km the air-equivalent can then be approximately calculated from formula (9).

$$\gamma = ps/D_0 \tag{9}$$

Here p is the total pressure measured in cm of mercury at the height, h, and s is the density of mercury. Values of r_h calculated from this formula are given in Table 9. Whether we assume the complete mixing to extend only to a certain height or throughout the atmosphere, the densities obtained in the auroral region will be somewhat uncertain because of lack of knowledge regarding the temperature above, say 38 km. The relative uncertainty increases upward but as long as we are below, say 100 km, the calculated density and total pressure are of the right order of magnitude.

Vegard [845, 1357] calculated the air-equivalent for various altitudes corresponding to the basic assumptions of Wegener regarding the distribution of matter in the atmosphere. The assumptions of Wegener are found to be erroneous because they lead to a hydrogen-helium layer on the top of the atmosphere. However, we should obtain the right order of magnitude of the total air-equivalent below 100 km by adding the effects of oxygen and nitrogen. The calculations of Vegard show that the total air-equivalent at an altitude of 100 km is of the order of magnitude of 0.2 cm, which corresponds to proton rays with an energy of about 160,000 electron-volts. The α rays from radium C with air-equivalent of about seven cm would stop at about 77 to 80 km. Now, the aurorae have been observed as low as 70 or perhaps 65 km, with air-equivalents of 20 to 43 cm (compare Table 9). To account for the observed minimum height of aurorae, any type of positive rays (even proton rays) would require energies of the same order of magnitude as that of α rays from radioactive substances. The corresponding value of the magnetic stiffness, $H\rho$, should be of the order of magnitude of 400,000. According to the calculations of Störmer (Table 9), such a magnetic stiffness, $H\rho$, would give nearly the right value for the angular diameter of the auroral zone.

(2) THEORETICAL DISTRIBUTION OF LIGHT-INTENSITY

Vegard [1360] calculated the distribution of light-intensity to be expected if the aurorae were produced by α rays or canal rays. The calculations were based on the assumption that the light-intensity along an α ray was proportional to the ionization. In the case of canal rays, the calculations were based on the excitation-function directly determined by Vegard [1356]. The calculations were carried out for neutral air and hydrogen, subject to a gravitational field. The results for air are shown in Figure 9, in which curve I corresponds to α rays and curve II to a heterogeneous bundle of canal rays. The theoretical curves were found to agree fairly well with certain aurorae, where the luminescence has a pronounced maximum near the bottom edge.*

These and certain other considerations led Vegard to the view that the aurorae were produced by positive rays. Later on, more systematic studies of the intensity-distribution along the streamers and of the auroral spectrum led to results which were best explained by the assumption that the solar electric rays producing the aurorae were principally composed of electrons. In the case of positive rays we may assume that each ray passes in a nearly straight line along the magnetic lines of force and that the scattering is negligible. In the case of electron rays, however, the scattering is large and the theory of the absorption and distribution of light-intensity is much more complicated. If we assume that the electron rays are absorbed in a homogeneous medium, according to an exponential law, the intensity, I_h, at a height, h, is

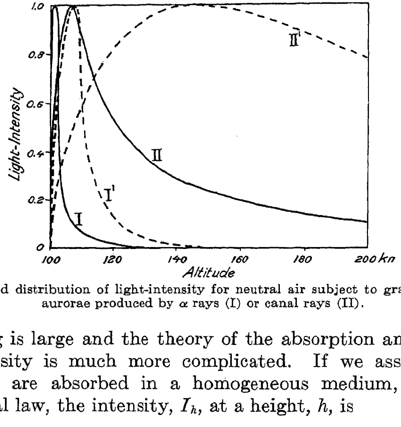


FIG. 9.—Calculated distribution of light-intensity for neutral air subject to gravitational field for aurorae produced by α rays (I) or canal rays (II).

$$I_h = I_0 \cdot \exp\ (\mu P_h/g) = I_0 \cdot \exp\ (-\mu m_h) \qquad (10)$$

where μ is the mass-absorption coefficient, m_h is the mass per unit-area traversed, and P_h is the total pressure at the height, h.

The diminution of cathode-ray intensity downward was first calculated by Lenard [1323]. Vegard [1360] determined the distribution of light-intensity on the assumption that the luminescence is proportional to dI/dh. If the auroral region is supposed to be composed of air for which the density varies according to the usual formula for height, the intensity of the cathode rays will vary as in curve I of Figure 10, while the intensity-luminescence will vary in accordance with curve II. It may be easily proved that the position of maximum light-intensity is determined by the relation, $\mu m_h = 1$.

---

* Curves I′ and II′ of Figure 9 are corresponding curves for a hypothetical layer of hydrogen, which in fact does not exist.

However, it is to be remembered that in a space with so low a density as that of the auroral region a bundle of parallel rays may preserve its direction of motion and cross-section for fairly large distances, in the same way as indicated by the experiments of Villard [1384] and Brüche [802]. In other words, the scattering effect may be very small for ray-bundles at low pressure and the calculation of Lenard [1323], based on complete scattering, is not applicable for the study of the distribution of luminosity but may be used to estimate the altitude which cathode rays of given velocity may reach.

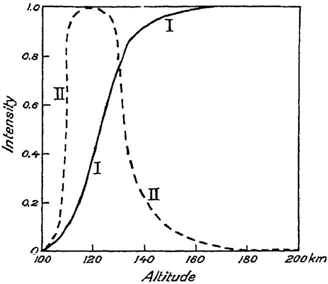


FIG. 10.—Distribution of intensity of cathode rays (I) and light-luminescence (II) supposing air-density varies according to usual formula for height.

(3) CONSEQUENCES TO BE INFERRED FROM THE DISTRIBUTION OF LUMINESCENCE

The study of the variation of light-intensity along the streamers described in Section I-9 revealed that the light-distribution curve varied not only with the auroral type but, even for the same type, showed large variations. Vegard, considering the possibility that the variation with type might indicate that the various types were produced by different types of electric rays, holds that such an explanation can hardly be brought into harmony with the fact that one type may change into another gradually. An arc may gradually develop into a drapery-shaped arc and then break up into draperies and ray-bundles.

If the rays are mixtures, as suggested by Vegard [1369, 1372, 1374], there is a possibility of gradual changes of the composition of the rays which may account for the variations of luminosity-distribution. As shown later, the distribution of matter within the auroral region may undergo considerable changes of density-distribution. These may account partly for differences shown at different times and localities, but they cannot explain the very considerable variations of intensity-distribution shown simultaneously at the same locality. The most immediate explanation suggested by such variations would be to assume that they correspond to changes in the *composition* of the solar ray-bundles, which then should be regarded as a mixture of corpuscles of different mass and velocity. Such an explanation would seem to involve very fundamental changes in the theory of Birkeland and Störmer. For, according to Birkeland's basic hypothesis and Störmer's calculations, the spot where the ray-bundles strike the Earth is a function of the magnetic stiffness of the rays; although we might conceive a change of composition of the ray-mixture to take place in such a way that the magnetic stiffness of the ray-bundle as a whole might be preserved, such an adjustment does not seem likely to occur, but we should expect the position of the aurora to change with the change of composition of the ray-bundle. In fact, we may observe great changes of luminosity-distribution within the same auroral form and without change of position.

Having come to the conclusion that changes of composition cannot be accepted, Vegard [845] developed a theory of the intensity-distribution along the auroral streamers, based on the assumption that the law of absorption of electric rays in the upper atmosphere of small density must be greatly influenced by the magnetic field of the Earth and by those of magnetic disturbances. If a narrow bundle of electric rays may move in the upper atmosphere for long distances without being essentially scattered and if it forms an angle with the magnetic lines of force, it will move in a screw line. The luminescence produced per unit-length in the direction of the auroral streamers will be proportional to the number of turns the bundle makes per unit-length measured along the lines of force; it will be a maximum when the bundle moves perpendicular to the lines of force.

The lines of force converge slightly and, for the small region of an auroral streamer, approximately to a common point, and the field is approximately equivalent to that of a single magnetic pole, placed at the point of convergence. In such a field an electric ray, according to Poincaré ["C.-R.," **123** (1896)], will move in an orbit which forms a geodetic curve on a cone of revolution, its top coinciding with the magnetic pole. The orbit will then move in a spiral, in such a way that the angle between the direction of motion and the magnetic lines of force increases, until the orbit is perpendicular, and then turns back into space.

Let us imagine a straight line drawn through the pole and parallel to the orbit of the ray infinitely far from the pole. The distance, d, between these two lines is then easily shown to be equal to the distance from the pole to the turning point [compare "C-R.," **123** (1896), and 845]. The total number of turns which a ray of given velocity makes on its way from infinity to the turning point is inversely proportional to the velocity of the ray. The angle, ψ, between the line of force and the orbit of the ray at a certain distance, r, from the pole is given by $\sin \psi = d/r$ and is seen to be independent of the velocity. The following important conclusion follows from this: If a narrow ray-bundle moves through matter, without being essentially deviated through scattering, it will move in such a way that, if the ray reaches the turning point, it will at this point have the same distance from the pole (point of convergence) as though the ray-bundle had moved with constant velocity without absorption. Near the turning point the light-intensity will be large on account of the great number of turns per unit-length and the intensity, at the point where the rays stop it, will be large because the number of molecules excited per unit-length of path has a sharp maximum near this point.

The height of the turning point or the point where the ray stops is a function of the distance, d, which is the same as a function of the angle between the orbit and the magnetic lines of force at the height where the ray may be said to enter the atmosphere, and this height increases with increasing angle. The various rays forming a streamer may enter the atmosphere under different angles varying from 0° to 90° and, according to the angular distribution of the rays, these will result in a different distribution of height of the points of turning and absorption, and there will result a different distribution of light-intensity along the streamers.

If a certain aurora were formed by rays which entered the atmosphere at a height, H, under a constant angle, ψ_0, the height, h, of the lower limit would be a function of ψ_0 and would increase with increasing value of ψ_0. If the angle at any point during the passage of the ray through the atmosphere is ψ_h and if it could be regarded as nearly constant during the interval where the predominant part of the absorption takes place, the air-equivalent, γ_h, corresponding to vertical incidence at any height would have to be multiplied by $(1/\cos\psi_h)$ to give the effective air-equivalent for that particular ray at the height considered.

If the ray entering the atmosphere has a penetrating power measured along the path equal to R_0 cm of air, the ray moving under an angle, ψ, with the lines of force reaches an altitude determined by the equation

$$\gamma_h/(\cos\psi\cos I) = R_0 \tag{10a}$$

where I is the magnetic inclination. If γ_h is found as a function of h, in the way previously shown, we can for a given value of R_0 determine the height for any type of rays as a function of the angle, ψ. When ψ approaches 90°, $\cos\psi$ approaches 0 and even a very small value of γ_h might give complete absorption. This means that when the ray spirals round the lines of force a sufficient number of times, a fairly small air-equivalent, γ_h, would be sufficient to bring the ray to absorption, provided the convergence of the lines of force do not make the ray return into space before absorption takes place. Thus rays of identical properties according to the value of ψ_0 may produce aurorae with their lower limit at different altitudes; the smallest altitude would correspond to $\psi_0 = 0$.

The formation of a long auroral ray means that a comparatively large number of the electric rays have large values of ψ_0. If practically no rays are parallel to this line of force, this means that the lower limit is larger than the minimum value corresponding to $\psi_0 = 0$. *In this way we explain the fact that the height of the bottom edge of the aurora increases as the length of the streamers increases.*

To illustrate our explanation of the light-distribution, we shall suppose that we know, for a given streamer, the relative number of orbits which enter the atmosphere in each angular interval of, say one degree. The relative numbers, n, as a function of ψ may then be represented in a diagram like Figure 11 with n as ordinate and ψ as abscissa. A distribution-curve like curve *a* would give an arc reaching the minimum altitude. Curve *b* would correspond to a drapery-shaped arc or drapery also reaching the minimum altitude. Curve *c* would correspond to a long ray-streamer which does not reach down to the minimum altitude. Curve *d* would correspond to an arc not reaching the minimum altitude.

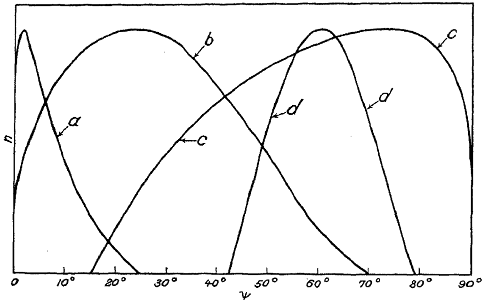


FIG. 11.—Relative number of orbits, n, as a function of angle with lines of force, ψ; curve *a* giving arc and curve *b* drapery or drapery-shaped arc reaching minimum altitude, curve *c* long ray-streamer and curve *d* arc not reaching minimum altitude.

As the angular distribution-curve may undergo rapid changes, we can understand the sudden variations with regard to intensity-distribution along the streamers and that ray-bundles, sometimes forming part of a drapery-shaped arc or drapery, may shoot below the average lower limit. At their turning points the electric rays move perpendicular to the lines of force and the radius of curvature of the orbit must be smaller than half the cross-section a of the auroral ray. Since $\rho = (mv/eH)$ and H is nearly 0.5 gauss, $(mv/e) < (a/4)$. Now we measure rays which have cross-sections less than one-half km, whence $(mv/e) < 1.2 \times 10^4$, or we may say that (mv/e) cannot exceed the order of magnitude 10^4.

From Bohr's formula for the penetrating power of positive rays as a function of charge, mass, and velocity, Vegard [845] concluded that a positive ray for which $(mv/e) < 10^4$ will not have sufficient penetrating power to account for the small values sometimes found for the height of the lower limit. Proton or α rays having sufficient penetrating power to reach down to, say 80 km, must have values of $(mv/e) > 4 \times 10^5$. Thus he was led to assume that the aurorae were formed by electron rays which, for values of $(mv/e) < 10^4$, may have sufficient penetrating power to penetrate to heights of 65 km or even less.

TABLE 10.—*Values of (mv/e) for heights, H, of penetration on the basis of absorption per equation* (10)

$v/c = \beta$	V, volts	$\dfrac{m_0 v}{e\sqrt{1-\beta^2}}$, emu	μ (International Critical Tables)	95 % absorption	
				P_h, cm	H, km
0.01	25.4	17	1.8×10^7	1.229×10^{-8}	136
0.1	2,560	171	8×10^5	2.764×10^{-7}	113
0.2	10,500	347	3.6×10^4	6.14×10^{-6}	108
0.3	24,500	535	2.9×10^3	7.63×10^{-5}	92
0.4	46,300	742	4.9×10^2	4.51×10^{-4}	79
0.5	78,600	981	2.2×10^2	1.01×10^{-3}	74
0.6	127,000	1,275	8.3×10^1	2.66×10^{-3}	68
0.7	203,000	1,666	2.9×10^1	7.63×10^{-3}	61
0.8	339,000	2,266	1.3×10^1	1.70×10^{-2}	55
0.9	657,000	3,509	6	3.69×10^{-2}	51

TABLE 11.—*Air-equivalents R_h*

h, km	P_h, cm Hg	$R_h = P_h s/D_0$, cm
0	76	7.96×10^5
10	19.2	2.01×10^5
20	4.13	4.13×10^4
30	8.92×10^{-1}	9.34×10^3
40	1.92×10^{-1}	2.02×10^3
50	4.15×10^{-2}	4.15×10^2
60	8.96×10^{-3}	9.39×10^1
65	4.16×10^{-3}	4.36×10^1
70	1.93×10^{-3}	2.03×10^1
75	8.98×10^{-4}	9.41
80	4.17×10^{-4}	4.37
85	1.94×10^{-4}	2.03
90	9.00×10^{-5}	9.43×10^{-1}
95	4.18×10^{-5}	4.38×10^{-1}
100	1.94×10^{-5}	2.03×10^{-1}
110	4.19×10^{-6}	4.39×10^{-2}
120	9.04×10^{-7}	9.47×10^{-3}
130	1.95×10^{-7}	2.04×10^{-3}
140	4.21×10^{-8}	4.41×10^{-4}
150	9.08×10^{-9}	9.51×10^{-5}
200	4.25×10^{-12}	4.45×10^{-8}
400	2.03×10^{-25}	2.13×10^{-21}

The correctness of this statement appears from Table 10, which gives the values of (mv/e) for heights, H, to which they should penetrate, on the assumption that the absorption follows the law expressed in equation (10) and that the pressure varies with the height according to Table 11. Table 11, which also gives the air-equivalents, R_h, is calculated on the assumption of perfect mixing and that, below ten km, the average temperature is 248°K and 223°K above ten km. On these assumptions, the equations (10*b*) and (11) hold.

$$P_h\mu = (1/s) \log \text{nat } 20 \tag{10b}$$

$$P_h = p_0 \cdot \exp (0.0045H) \cdot \exp [-H(h/223)] \tag{11}$$

R_h is calculated from equation (9), P is the pressure in cm of mercury, μ is the mass-absorption coefficient, s is the density of mercury, and $H = 10^5(28.95g/R) = 14{,}852$ when h is in km.

Although the distribution of matter above 90 km is very uncertain, the values for this altitude no doubt give the right order of magnitude, and we notice that cathode rays must have energies of the order of magnitude of at least 10^4 electron-volts in order to penetrate to 100 to 110 km—the most frequent height of the lower limit of aurorae. Above 80 km these values derived from equation (11) and Table 11 are in fact too small, because of an electric influence to be dealt with later.

(4) THE SOURCE OF ELECTRIC RAYS

By some process or other, the electric rays must be emitted from the Sun. From the appearance of aurorae and magnetic disturbances, Birkeland concluded that they formed fairly limited bundles of rays of very high velocity, originating from sunspots or their vicinity, and he discussed various possibilities for the formation of these bundles. Arrhenius [797] assumed that the electric rays were driven away from the Sun by the pressure of the sunlight. Vegard [1356] showed that the light-pressure theory in this original form met with difficulties, because the forces derived from Lebedew's experiments on gases were found to be too small even to counterbalance gravitation.

In 1926 Milne [1330] showed that the light might give sufficient effect to produce outward motion if he took into account the change of wave-length of the absorption-lines due to Doppler effect. However, an electric radiation, produced in this way, cannot be considered as the cause of the aurorae and polar magnetic storms. The electric radiation, being produced by the pressure from the thermal light-emission from the Sun, must go on continuously. The Earth should be under the influence of a fairly constant source of radiation, and the aurorae shoulb de a phenomenon appearing quite as regularly as the ordinary sunlight. In addition, the velocities produced can hardly exceed 10^8 cm/sec and would be too small to account for the average and minimum height of the lower limit of the aurora. The energy is mainly associated with the moving charged atoms and we saw that, in the case of positive rays, energies larger than those of α rays from radium C would be required to account for the lowest aurorae.

As pointed out by Vegard [1360], a radiation of material particles due to the pressure of light might explain only very regular phenomena, like the diurnal variation of the magnetic field and the zodiacal light.

The hypothesis of Birkeland was criticized by Schuster [327, 436], who found that limited bundles of rays of particles carrying a charge of the same sign could not escape from the Sun because their motion was counteracted by electromagnetic forces due to the motion and that the formation of limited bundles would be prevented because of the mutual electrostatic repulsion. These difficulties were discussed by Vegard [1360] who also concluded, from other considerations, that the Sun at any moment must emit equal amounts of positive and negative electricity. The geographical and diurnal distribution of aurorae and magnetic storms, however, shows conclusively that the ray-bundles forming them must be deflected in a definite way in the Earth's magnetic field as though they were composed of particles of one sign of charge.

To meet the criticism of Schuster and to account for the existence of current-systems round the Earth, which according to Birkeland and Störmer might explain the equatorial magnetic storms, Vegard [1360] found that the ray-bundles ought to be electrically neutral. All necessary conditions are fulfilled if we assume that *the rapidly moving particles which are responsible for the deviation suffered in a magnetic field may be mainly of one sign, for example, electrons, but that the ray-bundle is electrostatically neutralized by very slowly moving particles of opposite sign.*

When a bundle of electric rays breaks out from the Sun, it will draw in ions of opposite sign from all sides and, during this process of neutralization, the bundle will be retarded in its motion; but when the neutralizing core of ions is formed, the electric rays will move through it without having their velocity essentially reduced. On account of the rapid motion of the ray-particles, the volume-density and the number of particles necessary for the neutralization will be small.

If we assume the rays to be formed by electrons moving with a velocity $v = c/2$, the total current to be $i = 10^9$ amp, and the cross-section, F, to be ten times the diameter of the Earth, the number of positive ions per cc necessary for neutralizing the bundle will be approximately

$$n = ic/10evF^2 = 10 \text{ per liter} \tag{12}$$

A beam of this constitution is just what we have in vacuum-tubes. Anyone who has worked with cathode rays knows that we can obtain long narrow bundles and that they maintain their small cross-section just because the track or core of the bundle is neutralized by positive ions. It is of interest to note that, although the ions along the track neutralize the electrostatic action, the electric rays will be deflected in a magnetic field as though the neutralizing ions were absent. Applied to the auroral problem, this means that such a neutral bundle in a stationary state will be deflected in the Earth's magnetic field, as though we were dealing with a single, moving, electrified particle (compare Brüche's experiments).

A more general case would be to suppose that the particles of opposite sign were also moving, in which case

$$i = ne(V - v) \tag{13}$$

where the velocity V is supposed to be large compared with v. The deflections of such a beam will be more complicated, but the track of the whole bundle should be mainly determined by that part which has the largest magnetic stiffness.

The two groups of corpuscles will mutually influence the orbits they assume in a magnetic field. As pointed out by Vegard [1369, 1372], the deflection of the bundle as a whole will be determined by a kind of average value of the specific charge. If we consider a bundle of larger cross-section, the various streamers within the bundle may have different values of the average specific charge ($\Sigma e/\Sigma m$) and therefore one streamer may suffer a deflection different from that of its neighbor. *If the average value of the specific charge undergoes a continuous variation within a bundle, the matter may be drawn out in the magnetic field into a drapery; each streamer of a drapery then should correspond to a definite average specific charge.* The variation of magnetic stiffness being due to change of average specific charge does not involve a change of velocity and penetrating power. This is in accordance with the fact [851] that the height may be the same all along the bottom edge of a long drapery.

The surplus electric charge of one sign, which leaves the Sun through such a bundle, must be compensated by solar streams of opposite sign; but these compensating currents may be formed by slowly moving particles emitted more or less from the whole surface of the Sun and need not be concentrated into narrow bundles.

Following the light-pressure theory of Milne and a suggestion of Lindeman [410], S. Chapman in a number of important papers [187, 377, 380, 381, 383, 387, 388, 804, 995, 996, 1232, 1234, 1315] developed the consequences of the emission of a neutral stream, so constituted that equal amounts of charge pass the cross-section in unit-time. When such a streaming cloud of ions comes under the influence of the magnetic field of the Earth, induced currents should be produced. This he thinks may account for certain types of magnetic disturbances. The aurorae and polar storms, however, cannot be accounted for by neutral streams of this kind, for as already mentioned these phenomena require that electric currents, which have a small cross-section compared with the diameter of the auroral zone, penetrate into or close to the atmosphere of the Earth.

In connection with a discussion of the formation of the solar corona, Vegard [1369] also suggested a possible explanation regarding the formation on the Sun of strong ray-bundles. Through the vortex motion, which is attached to the sunspot-activity, masses from the interior are supposed to be brought up to the surface. These masses have a large store of energy and may be highly ionized. Through the recombination-process which takes place near the surface, light of very short wave-length of the type of X rays may be formed and electrons of high speed will result through photoelectric action. The emitted electrons take the form of a narrow bundle because the effective source is very limited and because the electron-rays will have a tendency to follow the lines of force of the local solar magnetic fields which are attached to the sunspots. The active masses, pumped up to the surface, may be very large and store much energy and may last during several revolutions of the Sun, thus explaining the fact that strong magnetic storms and aurorae reappear after 27 days and may continue to do so after several revolutions and after any visible trace of the original sunspot-group has disappeared.

(5) RELATION BETWEEN AURORAE AND MAGNETIC DISTURBANCES AND THE POSITION OF THE AURORAL ZONE

The geographical and diurnal distribution of polar magnetic storms shows that the ray-bundles producing them must suffer large deviations in the Earth's magnetic field for distances which are large compared with the dimensions of the Earth. Thus the ray-bundles themselves carry an electric current and produce a magnetic field. When these currents come near the Earth, they produce direct magnetic effects which form the primary and probably the most essential part of the perturbing fields. This applies first of all to the polar storms; but if the ray-bundles are the seat of electric currents, they must produce magnetic effects as soon as they come near the Earth even though the rays do not penetrate sufficiently near its surface to form polar storms.

This was the view taken by Birkeland, who considered not only the polar storms but also equatorial and perhaps the cyclo-median storms as primarily caused by the magnetic effect of the currents carried by the electric ray-bundles, the difference being mainly that the equatorial storms are produced by systems near the magnetic equatorial plane at a distance from the Earth many times its diameter. If the ray-bundles are electrostatically neutralized in the way described, stationary current-systems, even in the form of a circular ring, may be formed by the ray-bundles producing the magnetic disturbances. The electrostatic neutralization is in agreement with the fact that aurorae and polar magnetic storms do not influence the Earth's potential-gradient. *This view accounts for the sudden and irregular appearance of the equatorial storms and that, as a rule, they develop gradually into a storm of polar type.*

With regard to the cyclo-median storms, Birkeland [66] found that they appeared on the dayside of the Earth, and from their form and the distribution of the perturbation-field he concluded that they were due to current-systems near to the Earth and situated somewhere in the upper atmosphere.

Recently McNish [416] has studied a certain type of magnetic disturbances which accompany the so-called "fade-out" phenomenon which is found in connection with radio-echo observations [977]. The character of these perturbations as regards time of appearance, duration, and field is in fact the same as that of the cyclo-median storms described by Birkeland. McNish points out that the perturbation-field has essentially the same form as that due to the diurnal magnetic variation.

According to the theory of the upper atmosphere developed by Vegard [847, 1372, 1374, 1380-*B*], which will be dealt with later, the "fade-outs" are caused by solar rays of short wave-length of the type of soft rays, and consequently the cyclo-median storms and also the diurnal magnetic variations are similarly caused by solar rays of the photon-type.

Thus this particular type of magnetic perturbation is not, as thought by Birkeland, caused by electric solar rays. *On the contrary they show us the type of perturbations which result from light of short wave-length* (ultraviolet light or X rays), and it proves definitely that neither the polar storms nor the aurorae are due to rays of the photon-type; thus the interpretation of the cyclo-median storms shows in a most direct way that *the ultraviolet-light theory of aurorae as proposed by Paulsen, Villard, and Maris and Hulburt is not valid.*

The aurorae should be produced by the same type of ray-bundles as those primarily producing the polar magnetic disturbances. Naturally this suggests the idea that the aurorae are the direct cause of the polar magnetic storms. A closer inspection shows, however, that the correlation is not so simple. From auroral observations made at Bossekop compared with simultaneous magnetic records from the same locality—Haldde—Vegard [1359, 1360] found that the hourly interval of strongest aurorae usually coincided with an interval of high magnetic activity; but finding cases where strong aurorae appear fairly near the zenith without marked magnetic effect, he concluded that the direct effect of the aurorae is comparatively small. Thus the greater part of the current-systems producing the polar storms is ineffective in producing auroral luminescence.

As far as the results of existing observational data go, the aurorae and polar magnetic disturbances differ as regards diurnal distribution. Although the aurorae have a maximum about one hour before magnetic midnight, the average polar magnetic storm is strongest three or four hours later. However, it must be remembered that the determination of the diurnal distribution of the aurorae is very unsatisfactory; it is possible that improved methods and better material may give a closer agreement between the aurorae and the magnetic disturbances in this respect.

During magnetic storms which accompany the aurorae, current-systems may be formed also at great distances from the Earth. Störmer [1338] has calculated the influence on the ray-orbits of a circular current-system concentric with the Earth and in the plane of the magnetic equator. According to theory, the radius of the system should be equal to the fundamental length, c, determined by equation (3). Störmer finds that such a system will have the effect of increasing the magnetic polar distance of the point where the rays strike the atmosphere or of increasing the radius of the auroral zone.

From the theory given for the distribution of light-intensity along the streamers, it followed that the aurorae were mainly produced by cathode rays, because (mv/e) was found to be less than 10^4. From Table 10 we find that for aurorae reaching 100 km, (mv/e) should be of the order of 300, and from Störmer's calculations (Table 9) the corresponding magnetic polar distance is only about three degrees. If then our interpretation of the intensity-distribution along the streamers is right, we have to assume that the orbits of the electric rays must be essentially different from those resulting only from the permanent magnetic field of the Earth. There must be some additional influences which essentially alter the orbits.

Störmer [1338] showed that a circular current-system in the magnetic equatorial plane will have the effect of increasing the radius of the polar zone, and we may specify the circular current so as to give the right polar distance of the auroral zone, independent of the value of (mv/e).

To explain certain differences regarding the variation of the auroral frequency near the auroral zone and at lower latitudes, Vegard [844] assumed that the aurorae were driven toward lower latitudes as the effect of the current-systems producing magnetic disturbances and that an intimate correlation existed between the strength of the magnetic storm and the distance of the aurorae from the magnetic axis-point. Following a suggestion by Vegard, A. Röstad undertook a systematic investigation of this correlation. Although the data from auroral observations for this purpose were somewhat unsatisfactory, the investigations of Röstad [432] showed that the magnetic polar distance increases in a very definite way with increase of magnetic storm-intensity as measured at Potsdam. The relation is indicated by a curve derived from Röstad's results as in Figure 12.

Therefore, it may be considered as proved that the polar distance is a function of the intensity of the magnetic disturbance in operation at the time, and it is possible that the radius of the zone of maximum frequency also may be essentially influenced by the perturbing fields. Thus we may obtain a sufficiently large angular diameter of the auroral zone, even if we suppose that the aurorae are produced mainly by electron rays for which $(mv/e) < 10^4$.

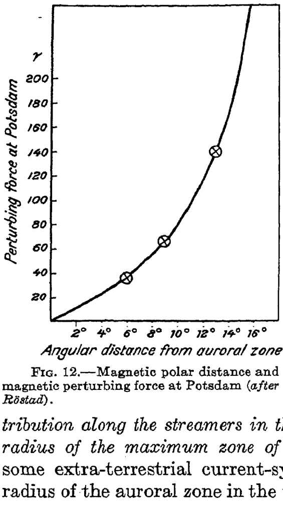


FIG. 12.—Magnetic polar distance and magnetic perturbing force at Potsdam (*after Röstad*).

However, relations found by Röstad (Fig. 12) indicate that an angular radius, equal to that of the maximum zone, should result when the perturbing force approaches zero. If this result is confirmed, it would mean that the large angular radius of the auroral zone of 20° cannot be due to perturbations and we should have to find some other explanation. Vegard [1369] has pointed out that if the ray-bundles from the Sun consist of cathode rays mixed with slowly moving positive rays, as given in equation (13), the average specific charge, $(\Sigma e/\Sigma m)$, will be diminished and the magnetic stiffness correspondingly increased. *A bundle of rays constituted in this way might at the same time account for the intensity-distribution along the streamers in the way described and give the right angular radius of the maximum zone of frequency.* Another probability is that some extra-terrestrial current-systems *existing permanently* increase the radius of the auroral zone in the way indicated by Störmer's mathematical calculations.

V. THE AURORAL SPECTRUM AND ITS INTERPRETATION

(1) SOME HISTORICAL REMARKS

If we look at an aurora of moderate strength through a spectroscope, we usually see only a strong green line. From the time when Ångstrom in 1869 detected the green line and until 1912, a considerable number of observations of the auroral spectrum were made by many observers. Of these we may mention Carlheim-Gyllensköld, who spectroscopically observed a considerable number of lines at Spitzbergen during 1882–83, and A. Paulsen [827] and J. Westmann [852], who obtained spectrograms in the region of short waves. The accuracy obtained with the small dispersion used was not satisfactory. A summary of the results of observations on the auroral spectrum during the first period until 1910 is given by H. Kayser in volume V of his "Handbuch der Spectroscopie." It appears from his summary that the accuracy of the wave-length determinations at that time was insufficient for any definite interpretation; he expresses the opinion that nothing can be said about the chemical origin of the lines appearing in the auroral spectrum. At that time $\lambda = 5570$ was accepted as the most probable wave-length of the green line. This value was found to be about seven Ångstroms too small and the errors of the fainter lines perhaps 50 to 100 Ångstroms.

During the winter of 1912–13 Vegard [843, 1359] observed at Bossekop with a spectroscope for wave-length measurements of fairly large dispersion and with a spectrograph having a dispersion about five times larger than those previously used. He found that the wave-length of the green line was several Ångstroms larger than previously assumed, and he obtained spectrograms of the stronger lines in the region of short waves. These were measured with accuracy sufficient to show that they belonged to the negative band-spectrum of nitrogen.

Spectroscopic observations of the green line were continued by Vegard [1361] at Oslo with a spectroscope which should give the wave-length with an error less than one Ångstrom. He found the value 5577.6 Ångstroms. Slipher [1336] made a spectrographic measurement of the night-sky luminescence which gave 5578.05 Ångstroms. On the basis of the results of Slipher and Vegard, Babcock measured the wave-length of the green line of the night-sky luminescence, which he took to be identical with the auroral line. He found the wave-length 5577.35 Ångstroms. Auroral spectrograms were obtained by Lord Rayleigh [1333] which confirmed the results obtained by Vegard at Bossekop.

In 1922 more systematic investigations on a somewhat larger scale were begun by Vegard and his collaborators, E. Tönsberg and O. W. Lund. Most of the work was done at Tromsö from 1922–26 and a few spectrograms were obtained at Oslo. Preliminary results were published in a number of papers [847, 848, 1362, 1364, 1365, 1366, 1368, 1370, 1371] and a complete account appeared in the "Geophysical Publications" of Norway [1374].

For these investigations three types of spectrographs, two with glass and one with quartz optical systems, were constructed and used. One of the small glass spectrographs is shown in Figure 13-*A* and the larger one in Figure 13-*B*. They had a Rutherford prism, a collimator-lens of large focal length, and a camera-lens of small focal length. This construction was adopted because the light-power of a spectrograph does not depend on the light-power of the collimator-lens. One of the boxes for the large spectrograph is shown in Figure 13-*C*.

The investigations on the auroral spectrum were continued by Vegard at the new Auroral Observatory at Tromsö with L. Harang and E. Tönsberg as collaborators. Several new spectrographs were built, one with quartz optical system and one with glass optical system. The latter was provided with proper means for adjusting the optical system and is shown in Figure 14-*A*. A grating spectrograph of very high light-power, especially for use in the infrared region, is shown in Figure 14-*B*.

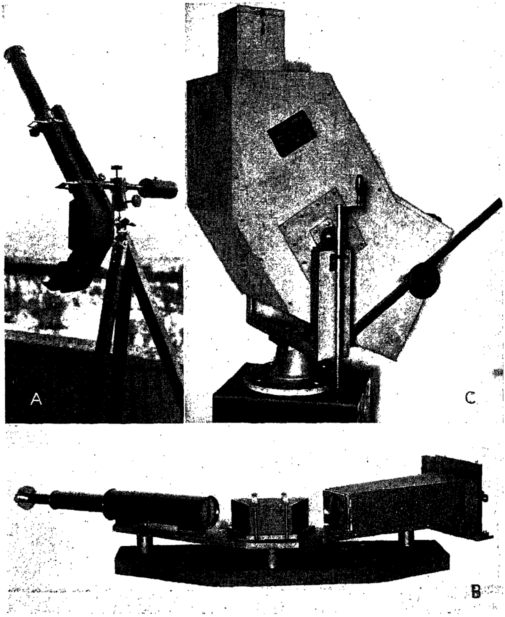


FIG. 13.—Various types of spectrographs.

Vegard and Harang have also undertaken precision-measurements of the stronger lines of the auroral spectrum using an interferometer-method. A large number of interferometer-photographs have been obtained for the green auroral line. It may be mentioned that the green auroral line is found to be identical with the green line of the night-sky luminescence and that no Doppler effect was found for the green line [1368, 1380]. Some results obtained at the new observatory were published in preliminary communications [1375, 1376, 1378]. A description of the new instruments and the results obtained during the first year's work appeared in two papers published in the "Geophysical Publications" of Norway [1379, 1381].

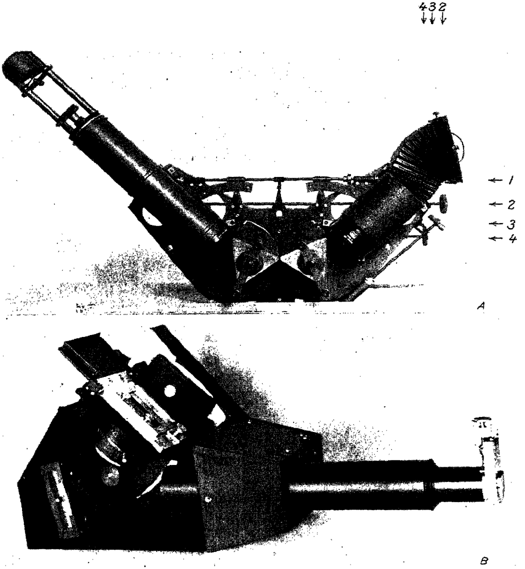


FIG. 14.—Spectrographs; (*A*) with adjustable glass optical system and (*B*) with grating of high light-power for use in infrared region.

(2) AUROLAL LINES OBSERVED AND MEASURED SPECTROGRAPHICALLY

A small collection of auroral spectrograms, which have been obtained by Vegard and his collaborators since 1922, are reproduced in Figures 15 and 16. Details regarding each spectrum of Figure 15 are given in Table 12 and of Figure 16 in its legend. All the auroral lines and bands, which have been observed and measured spectrographically by Vegard and his collaborators, are collected in Table 13. The wave-length given for any line is the mean value of the most accurate determinations. The accuracy differs for different lines and is smallest for those lines which are so faint that they have been obtained only on spectrograms taken with instruments of fairly small dispersion. The published papers supply all details.

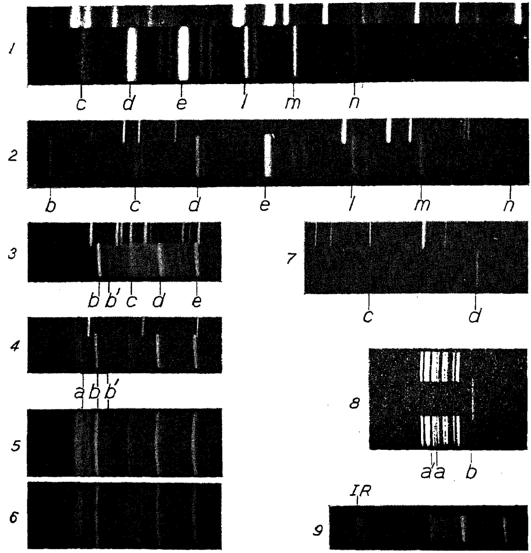


FIG. 15.—Auroral spectrograms (for details see Table 12) 1, 2, 3, 4, and 7 at Tromsö and 5, 6, 8, and 9 at Auroral Observatory, Tromsö; for wave-lengths of lines marked *a*, *b*, *c*, *d*, *e*, *l*, *m*, and *n* see Fig .16; *IR* on No. 9 = infrared bands.

The wave-length given for the strong green line is that obtained from interferometer-measurements by Vegard and Harang [1381-*A*] and which, within the limit of error, is the same as that found by Babcock for the light of the night sky [1309]. The value for the strong red line (6300.300) is taken from recent interferometer-measurements made at Oslo and Tromsö by Vegard and Harang [1381-*B*].

The lines and bands in yellow, red, and infrared are somewhat less accurate, partly because the dispersion used is smaller and partly because the spectrum in this region is mostly composed of bands which cannot be separated into their component lines, but they have the appearance of broad bands which do not have such sharp edges as those appearing in the region of short waves. For the lines and the sharper bands in yellow and red, the error does not exceed two to three Ångstroms. In the infra-

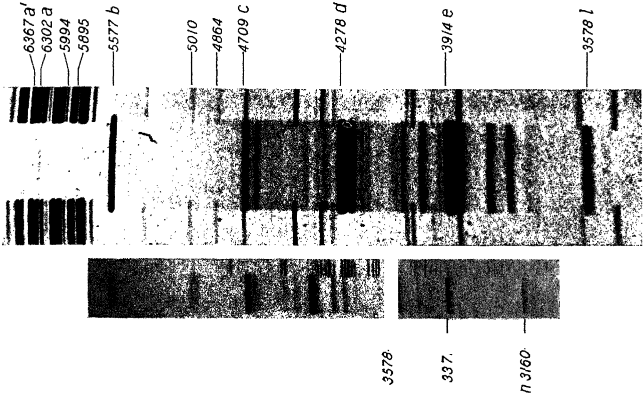


FIG. 16.—Auroral spectrograms; A = auroral spectrum at Auroral Observatory, Tromsö, with new large glass, spectrograph (Fig. 14A) using panchromatic plates, winter, September, 1931 to February, 1932, and (He—Ne) spectrogram for comparison; B = spectrogram obtained at Auroral Observatory Tromsö, with new large quartz spectrograph with two prisms, during winter, 1930–31, and Fe spectrum for comparison.

TABLE 12.—*Details of spectrograms shown in Figure* 15

No.	Spectrograph	Date	Effective exposure	Photographic plate	Comparison spectrum
1	Quartz with one prism	Sept. 27–Feb. 11, 1922	15 hours 17 minutes	Imperial Eclipse	Cd spark
2	Quartz with two prisms	Jan.-Apr., 1924	64 hours	Imperial Eclipse ortho	Cd spark
3	Small glass (Fig. 13)	Dec. 10–30, 1926	15 hours	Treated with pinaflavol	He tube
4	Small glass (Fig. 13)	May 10–Aug. 12, 1926	40 hours	Panchromatic B	He tube
5	Small glass (Fig. 13)	Mar. 18–19, 1933	4 hours	Illford hypersensitive	
6	Small glass (Fig. 13)	Mar. 19, 1933	1 hour	Illford hypersensitive	
7	Large glass (Fig. 14)	Oct. 9–Dec. 31, 1923	44 hours	Imperial Eclipse	He tube
8	Large new glass (Fig. 16)	Nov. 22, 1932	A few hours	Panchromatic	Ne tube
9	Small glass (Fig. 13)	Oct. 15–20, 1932	A few hours	Agfa 700–900$\mu\mu$	

TABLE 13.—*Auroral lines and bands observed and measured spectrographically* 1913–37 (Vegard and collaborators)

λ	*I*	Interpretation
8132	.....	1 *P G* 5– 4 6– 5
8035		
7906	47	1 *P G* 7– 6
7867		
7734	.....	1 *P G* 8– 7, (2–0)
7594	.....	1 *P G* 9– 8, (3–1)
7479	.....	1 *P G* (10– 9), 4–2
7368	.....	1 *P G* (11–10), 5–3
7264	.....	1 *P G* 6–4
7068	.....	1 *P G* 8–6
6861	.....	1 *P G* 10– 8, 3–0
6784	.....	
6768		1 *P G* 11– 9, (4–1)
6753		
6696	.....	1 *P G* 5–2
6682		
6669		1 *P G* 12–10
6619	40	
6605		1 *P G* 6–3
6592		1 *P G* 13–11
6543	.....	
6526		1 *P G* 7– 4
6512		1 *P G* 14–12
6469	.....	1 *P G* 8– 5
6454		
6441		1 *P G* (15–13)
6398	.....	1 *P G* 15–13 *O*I ($^1D_2 - {}^3P_0$)
6363	.....	1 *P G* (9–6) *O*I ($^1D_2 - {}^3P_1$)
6300.3	28	1 *P G* (10–7) *O*I ($^1D_2 - {}^3P_2$)
6185	.....	1 *P G* 12– 9
6129	.....	1 *P G* 5–1
6108	.....	1 *P G* 13–10
6068	.....	1 *P G* 6–2, ϵ(3–18)
6058	.....	1 *P G* 6–2
6011.1	.....	1 *P G* 7–3
6001	.....	1 *P G* 15–12
5990.8	15	1 *P G* 15–12
5966.4	.....	1 *P G* 8–4
5891	.....	1 *P G* 9–5, *N*II(5892.5)
5867	13	1 *P G* 17–14
5833	.....	1 *P G* 10–6
5751	.....	12–8, ϵ(1–16), *N*II(5754.8)
5577.3445	100	*O*I($^1S_0 - {}^1D_2$)
5238	6.0	1 *P G* 16–11 N_2B (5–18)
5002	.....	*N* (5002.7), nebulium
4858	.....	*O*II (4857,4861), *N*II (4860)
4780	.....	*N*II (4780), *O*II (4779), ϵ(5–17)
4708.7	7.8	*N G* 0–2
4652.2	4.6	*N G* 1–3 ϵ(4–16)
4596.1	3.4	*N G* 2–4

TABLE 13.—*Auroral lines and bands observed and measured spectrographically* 1913–37—(*Continued*)

λ	*I*	Interpretation
4566.0	.....	*N*II (4565)
4550.8	2.0	*N G* 3– 5
4535	1.6	ϵ(3–15)
4507	1.2	*O*II (4506.5)
4484	1.6	*N G* 5– 7 (*CB*) *N*I(4484.4)
4437	1.6	*O*II
4424	3.0	ϵ(2–14)
4415.1	2.5	*O*II (4414.9–4417.0), 2 *P G* (3–8) (4416)
4375.6	1.6	*O*II (4376.2), ϵ(5–16)
4368.2	2.4	*O*II (4369.3–4366.9), *O*I(4368.3)
4362.0	1.2	*O*II (4359.4), *N*I (4358.3), *O*III(4363.1)
4345.6	3.0	2 *P G* (0– 4)
4319.5	1.6	$b'\epsilon$(1–13)
4277.6P	24.4	*N G* (0– 1)
4267.6R		
4236	5.9	*N G* 1– 2
4226.3	4.0	*N*II (4227.8), *N*I (4224.7)
4218	3.0	ϵ(0–12) *CB*
4200.0	2.0	*N G*, (2– 3)
4176.2	1.4	ϵ(3–14)
4142.6	1.4	2 *P G* (3– 7), ϵ(6–16)
4119.7	1.6	*O*II (4119.2)
4092.0	1.6	2 *P G* (4– 8), *O*II (4092.9), *N*II (4092.7)
4076.0	.....	ϵ(2–13), *O*II (4076)
4058	3.4	2 *P G* 0– 3
4048.5	.....	*O*II (4048.2), ϵ(5–15)
3997.7	3.7	2 *P G* 1– 4
3981	1.0	$b'\epsilon$(1–12)
3942.8	2.2	2 *P G* 2– 5, ϵ(4–14), *O*I(3947.5)
3914.4P	47.4	*N G* 0– 0
3903.5R		
3884.5	2.2	*N G* 1– 1
3872.0	1.0	*O*II (3872.5)
3805.4P	4.9	2 *P G* 0– 2
3801.0R		
3769	1.0	ϵ(2–12)
3755.2	4.2	2 *P G* 1– 3
3728.6	1.0	*O*II (3726.1–3728.9)
3711.1	2.4	2 *P G* 2– 4
3708.0	.....	*O*II (3712.8)
3685.3	1.6	$b'\epsilon$(1–11)
3671.8	.....	2 *P G* (3– 5)
3603.0	1.0	ϵ(0–10)
3583	1.6	*N G* 1– 0
3577.6P	9.8	2 *P G* 0– 1
3570.0R	.....	2 *P G* 0– 1
3563.5	1.6	*N G* 2– 1
3536.8P	4.9	2 *P G* 1– 2
3531.5R	.....	2 *P G* 1– 2
3503.2	2.2	2 *P G* 2– 3

TABLE 13.—*Auroral lines and bands observed and measured spectrographically* 1913–37–(*Concluded*)

λ	*I*	Interpretation
3484	1.0	2 *P G* 7– 8
3468.7	3.0	2 *P G* 3– 4, *N*I(3470.2)
3429.0	2.0	$b'\epsilon$(1–10)
3371.3	9.0	2 *P G* 0– 0
3339.3	1.2	2 *P G* 1– 1
3285.3	1.8	2 *P G* 3– 3
3202.7	2.2	$b'\epsilon$(1– 9)
3192.4	.....	ϵ(4–11), *O*II (3194.9)
3168.7	.....	2 *P G* (9– 7)
3159.3P	5.8	2 *P G* 1– 0
3135.2R	.....	2 *P G* 1– 0
3125.7	3.6	2 *P G* 2– 1, ϵ(6–12)
3114.0	.....	2 *P G* 3– 2

red part the error may be even somewhat larger, at any rate for some of the fainter bands.

(3) INTERPRETATION OF THE AURORAL SPECTRUM

The auroral spectrum, apart from the strong green line and some usually faint lines, is dominated by the band-spectra of nitrogen. The first positive group dominates as a rule the red and infrared region. Only in the case of a certain type of red aurora, which will be treated later, a few red lines may be enhanced and become dominant in the red part. In the blue and violet the negative nitrogen group is predominant and in the ultraviolet the second positive group takes the lead.

The interpretations of the observed lines and bands are given in the third column of Table 13.

1 *P G*, 2 *P G*, and *N G* indicate the first and second positive group and the negative group of nitrogen, respectively. For each band is given the vibrational quanta numbers for the transition. *O*I and *N*I indicate spectral lines from the neutral oxygen and nitrogen atom, respectively; *O*II and *N*II indicate lines from singly ionized oxygen and nitrogen atoms. *C B* indicates bands observed by Vegard in the luminescence from solidified gases. ϵ indicates a band-system discovered by Vegard in 1924 in the luminescence from solidified nitrogen and which was shown by him to originate from the forbidden transition, $A^3\Sigma - X^1\Sigma$, of the nitrogen molecule. $X^1\Sigma$ is the normal state and $A^3\Sigma-$ is the metastable state which forms the bottom state of the first positive group.

It is a remarkable fact that one of the ϵ-series, $\epsilon(1,n)$, which originally was indicated by b', was shown to appear quite distinctly in the auroral spectrum [1379]. In this way Vegard showed for the first time [1327] that the ϵ-system at very low pressure could be emitted from nitrogen in the gaseous state. The wave-length of b'- or $\epsilon(1,n)$-bands as observed from the solidified state and those of the corresponding auroral bands are given in Table 14.

TABLE 14.—*Wave-lengths b' or $\epsilon(1,n)$-bands and corresponding auroral bands*

b'- or $\epsilon(1,n)$-bands	4719	4324	3985	3688	3429	3202
Auroral bands	....	4320	3981	3685	3429	3203

We notice from Table 13 that in addition to the b'- or $\epsilon(1,n)$-bands a number of other bands belonging to the ϵ-system appear also in the auroral spectrum.

The Balmer series of hydrogen does not appear. One very faint line appears near H_β, but this line may be referred to nitrogen or oxygen and, as we find no trace of H_α, this auroral line is not to be referred to hydrogen. A few lines nearly coincide with the lines of the helium series but, from considerations regarding the relative probability of these lines with helium lines not present, Vegard [1379] finds these approximate coincidences are accidental.

Thus the spectral lines of the light gases, hydrogen and helium, are probably absent in the auroral spectrum or, at any rate, extremely weak. Vegard, partly in collaboration with L. Grimestad, has studied the relative intensity of hydrogen respective to helium when mixtures of one of these gases with nitrogen are exposed to cathode rays. These experiments led to the result that the presence of only a few per cent hydrogen or helium in the upper atmosphere ought to have been detected.

The exploration of the auroral spectrum, including even very faint lines, led to the result, announced by Vegard in 1923 [847, 1362], that the layer of light gases, which on the basis of theoretic calculations had been supposed to be present on the top of our atmosphere, does not exist.

Another band or group of lines which has attracted a great deal of attention is the so-called second green line, which may be seen in the spectroscope for somewhat intense aurorae. A spectrogram showing this line was first obtained by Vegard [1368, 1371], and a very successful spectrogram of January, 1927 (reproduced as No. 3 in Figure 15), shows it distinctly. This spectrogram gave the wave-length 5238. The second green line was shown to be composed of several lines not separated. The value given corresponds to the maximum of photographic density. From an auroral display appearing at the Lowell Observatory, Arizona, July 7, 1928, Slipher and Sommer obtained, with a small spectrograph of high light-power, auroral spectra showing the second green line. They give it a wave-length 5206, which they interpret as an *O*I-line. Later Vegard and his collaborators obtained several spectrograms of the second green line (for example, No. 5 of Figure 15) and all give a wave-length between 5238 and 5240 for this line.

The outstanding problem regarding the auroral spectrum has been the interpretation of the strong green line. A great many suggestions were made, one of which was that it belonged to a light unknown gas, geokoronium. In 1923 Vegard investigated the variation of the intensity of the green line relative to that of the negative nitrogen bands, as a function of altitude, and found that it diminished upward. This result showed that the strong green line cannot be emitted from a gas lighter than nitrogen. The decrease of relative intensity upward would suggest that the gas which emits the green line is somewhat heavier than nitrogen, but such a conclusion—when seen in relation to the conditions existing in the auroral region—is not valid, since probably perfect mixing exists throughout the atmosphere; again the relative intensity within a spectrum from the same gas may be a function of pressure.

As the nitrogen bands were so prominent in the auroral spectrum, it would seem likely that the green line was also emitted from nitrogen in the peculiar state in which it might exist at the limit of our atmosphere. Having discussed various possible states of nitrogen, Vegard concluded that possibly the condition resulted from the existence of a very low temperature. Acting upon this idea, he began investigations at the Kamerlingh Onnes Laboratory at Leiden on the luminescence emitted when solid nitrogen and other solidified gases were bombarded with cathode rays. These investigations led to the discovery of a large variety of band-spectra. It was found that solid nitrogen emitted a strong band (N_1) in the region of the green auroral line as well as some other bands (N_2,N_3,N_4), which might account for the second green line, and some auroral bands in red.

To realize as nearly as possible the conditions which might be supposed to exist in the upper atmosphere, Vegard produced systems where particles of crystalline nitrogen were suspended in a solid layer of inert gas. Now it appeared that when neon contained traces only of nitrogen, the N_1-band assumed the shape of a diffuse line with a wave-length, 5577.8 which, within the limit of error, coincides with that of the green auroral line. The band, N_2, under similar conditions had its strongest component with a wave-length 5236 to 5238 which, within the limit of error, coincides with the second green auroral line. When we remember that in both spectra we are dealing with a few outstanding lines and bands, these coincidences are remarkable and probably too close to be accidental.

The bands, N_1, N_2, N_3, and N_4, are phosphorescent bands and, although they are observed in very pure nitrogen, the possibility remains that they may be essentially stimulated by the presence of minute quantities of another gas, for example, oxygen. At any rate, it is likely that, when we reach a more perfect understanding of the physical nature of the emission from solid nitrogen, it will appear that the bands, N_1, N_2, N_3, and N_4, are in some way related to the auroral spectrum. As already mentioned, this does not necessarily imply that nitrogen in the auroral region exists in the form of solid particles.

The luminescence from solidified gases and its interpretation have been the subject of extensive investigations by Vegard and later on also by McLennan and his collaborators [1325, 1327, 1363, 1367, 1377]. In 1925, McLennan and Shrum [1328] discovered a new oxygen-line, which they assumed to be identical with the green auroral line. This interpretation has been strengthened by later very accurate measurements, which gave $\lambda = 5577.34$ for the wave-length of the new oxygen line. It was shown to belong to the OI-spectrum and to correspond to a forbidden transition $^1S_0 \rightarrow {}^1D_2$. The system of energy-levels of the normal atom of oxygen is now quite well known, and this is shown especially in the works of Frerichs [1316] and Hopfield [1321]. Figure 17 gives a level-diagram of oxygen I, constructed after that given by Frerichs.

An extensive series of very accurate wave-length measurements of the green line carried out by Vegard and Harang gave the wave-length $\lambda = 5577.3445$, which agrees well with the wave-length found for the green OI-line ($^1S_0 \rightarrow {}^1D_2$) and shows that the green auroral line is the same as the green line appearing in the night-sky luminescence.

The oxygen atom, after the transition resulting in the 5577-line, is left in the $^1D_2$-state, which is also metastable, and we should expect to observe some lines corresponding to the transitions from $^1D_2$ to the normal $^3P_{012}$-state (compare Fig. 17). The wave-lengths of this triplet were derived indirectly by Frerichs [1316]; later some corrections were given by Hopfield and they were observed by Paschen. Transition $^1D_2 \rightarrow {}^3P_2$ gives $\lambda = 6300.27$ Ångstroms; transition $^1D_2 \rightarrow {}^3P_1$ gives $\lambda = 6363.73$ Ångstroms; and transition $^1D_2 \rightarrow {}^3P_0$ gives $\lambda = 6391.68$ Ångstroms. The lines are placed in the order of their intensity.

A line with a position near 6300 was observed with spectroscopes and was obtained on spectrograms by Vegard in 1923; it was particularly strong on spectrograms from red-colored aurorae which appeared in 1926. One of these spectrograms is shown by No. 4 in Figure 15. The line a is the line near 6300—its enhancement produces the red-colored aurora of type A. Spectrograms obtained at the Auroral Observatory, Tromsö, with instruments of higher dispersion gave the red lines for which we find the wave-lengths 6302, 6367, and 6398. Spectrograms showing these red lines are reproduced by No. 8 in Figure 15 and by A in Figure 16; the two stronger ones are visible on the reproduction.

These values are all somewhat larger than those given for the three lines of oxygen. The difference is considerably larger than the error which we should get with the instruments used, provided we were measuring sharp lines obtained in ordinary work in the laboratory. In auroral observations the error may be somewhat larger for two reasons. The regulation of temperature during the exposures, which last for days and even weeks, may not be quite perfect; the red lines nearly coincide with bands of the first positive group of nitrogen. If the lines of oxygen really appear in the auroral spectrum, they are mixed with these bands and thus appear to be broader than an ordinary sharp line would be. This broadening may not be symmetrical and in this way we may account for the differences between the wave-lengths of the red oxygen lines and the corresponding auroral lines. As the differences of wave-length are nearly right and as the relative intensities seem to agree, it is very probable that the red OI-triplet, ${}^1D_2 \rightarrow {}^3P_{012}$, really appears in the auroral spectrum.

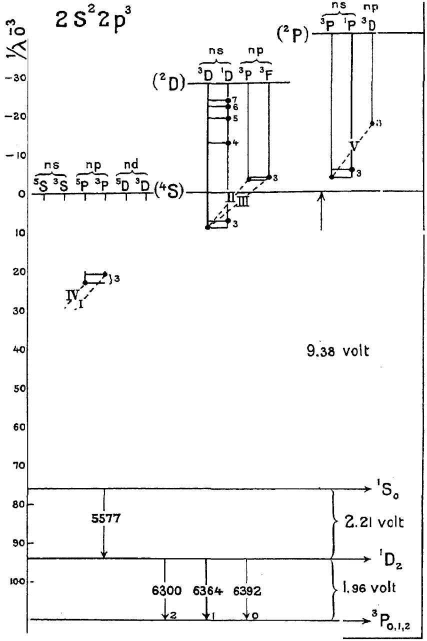


FIG. 17.—Energy-level diagram of oxygen I (*after Frerichs*).

During the years 1933–36, Vegard and Harang [1381-*B*] succeeded in obtaining a number of interferometer-pictures of the strongest component of the red *O*I-triplet. The observations were made partly at Oslo and partly at the Auroral Observatory, Tromsö. The interferometer consisted of Fabry-Perot quartz étalons placed in front of a camera lens. By using étalons of different thicknesses it was possible to fix the wavelength without ambiguity. The measurements at Oslo gave $\lambda = 6300.286$ and those at Tromsö $\lambda = 6300.312$. The mean value, 6300.300, is given in Table 13.

The interferometer-measurements of the green and red auroral lines show conclusively that the green line is identical with the oxygen line, $OI(^1S_0 \rightarrow {}^1D_2)$, and that the red oxygen triplet, $OI(^1D_2 \rightarrow {}^3P_{012})$, appears in the auroral spectrum.

McLennan's interpretation of the green auroral line requires a comparatively large number of atoms of oxygen to exist in the $^1S_0$-state. From the appearance of strong negative nitrogen bands, as well as from the altitude of aurorae, we know that the solar electric rays have more than sufficient energy to ionize the atoms of oxygen completely and therefore to bring them into the higher energy-states indicated in Figure 17. The transitions between these upper levels would give us, in the visible and infrared part, a number of *O*I-lines usually found by experiments in the laboratory, for example, when oxygen is bombarded with electric rays. Some of the prominent infrared *O*I-lines and the energy-levels to which they refer are given in Table 15 and are indicated in Figure 17.

TABLE 15.—*Prominent infrared OI-lines*

λ	Transition
I. 8446.4	$(^4S)3s\,^3S_1 \rightarrow (^4S)3p\,^3P$
8233.1	$(^2D)3s\,^3D_{123} \rightarrow (^2D)3p\,^3P$
II. 8230.1	
8221.8	
7952.2	$(^2D)3s\,^3D_{123} \rightarrow (^2D)3p\,^3F_{234}$
III. 7950.8	
7947.6	
7775.7	$(^4S)3s\,^5S_2 \rightarrow (^4S)3p\,^5P_{321}$
IV. 7774.0	
7772.0	
7481.3	$(^2P)3s\,^3P_{012} \rightarrow (^2P)3p\,^3D_{123}$
V. 7479.2	
7476.6	

In the auroral luminescence, however, none of these infrared *O*I-lines have been observed, although they fall in the region explored. The *O*I-lines which appear strong when oxygen is bombarded with electric rays are not found in the auroral spectrum, and those few auroral lines which fall near OI-lines may also be interpreted as N-lines and, at any rate, they are very weak.

In order then to explain the prominent strength with which the green line and, in certain cases, also the red OI-triplet appear in the auroral spectrum, we shall have to find some types of excitation-process, which would bring a large number of oxygen atoms into the ${}^1S_0$- and the ${}^1D_2$-state. Vegard [1379, Section 22] assumed that most of the energy radiated from the OI-atom does not come from a direct excitation by the solar electric rays but indirectly through collisions of the second kind with nitrogen in a state of abnormally high energy. He mentions two processes of this type which might be considered.

After the emission of the first positive group, the nitrogen molecule is left on a metastable level, A. The energy of this level, previously assumed to be about eight volts, is according to Vegard only 6.19 volts. On the other hand, the energy necessary to dissociate an oxygen molecule and to bring an atom of oxygen to the ${}^1S_0$-level is $5.1 + 4.2 = 9.3$ volts.

A nitrogen molecule in the A-state (N_2^A) has not sufficient energy to excite the ${}^1S_0$-state directly from normal oxygen molecules. As we know, however, some of the oxygen exists in the form of ozone and some in the atomic state; from these states N_2^A might excite the ${}^1S_0$-state in accordance with the equations

$$N_2^A + O_3 = O_2 + OI({}^1S_0) + N_2 + \epsilon \tag{14}$$

$$N_2^A + O = OI({}^1S_0) + N_2 + \epsilon \tag{15}$$

where ϵ is the surplus energy not spent in excitation.

The latter process, as in equation (15)—excitation of atoms of oxygen in the atmosphere—cannot be considered. From the laws of chemical equilibrium Chapman [1232, 1234] found that the concentration of atomic oxygen relative to that of the oxygen molecules and, certainly also in relation to that of the nitrogen molecules, must increase upward. If the production of the auroral line was mainly due to excitation of oxygen atoms, either through collisions of the second kind, as in equation (15), or directly through the impact of solar electric rays, we should expect the intensity of the green auroral line relative to that of the negative N_2-bands to increase upward; but this does not agree with the altitude-effect consisting of a considerable intensity-variation *in the opposite direction* [compare Section IV-2]. On the other hand, the process of equation (14), starting from ozone, would be in harmony with the altitude-effect, as the concentration of ozone relative to that of nitrogen, according to Chapman [1232, 1234], should decrease upward.

Another, and perhaps the most probable process suggested by Vegard [1379], consists in the excitation of normal O_2-molecules by means of "active nitrogen." In this connection, it is not necessary to adopt any definite opinion as to the nature of active nitrogen. It is sufficient to utilize the experimental result that the energy of active nitrogen, which is available for the excitation of other molecules or atoms, is found to be $E_a = 9.55$ volts. This energy by proper collisions with O_2-molecules may be transferred according to equation (16).

$$E_a + O_2 = O\text{I} + O\text{I}({}^1S_0) + \epsilon \qquad (16)$$

In this case the surplus energy, ϵ, is only 0.25 volt and, as the energies involved in the process nearly balance, the probability of the transfer is increased by "resonance."

In this way, we may understand that these few lines of oxygen may appear with considerable intensity although no other OI-lines appear and in spite of the small relative concentration of oxygen. The energy of excitation is primarily taken from the electric rays by the predominant gas—nitrogen—and then by a collision of the second kind, which is facilitated by resonance, the energy is absorbed by oxygen according to equation (16) and is finally reemitted.

By the processes indicated by equations (14) and (16) there might be also a certain probability for the transfer of one atom of oxygen to the ${}^1D_2$-state. On account of the effect of resonance, the process expressed by equation (16) will have a much larger probability than

$$E_a + O_2 = O\text{I} + O\text{I}({}^1D_2) + \epsilon' \qquad (17)$$

and the latter ought to be insignificant. For the ozone process, however, it might be possible that an excitation according to the equation

$$N_2^A + O_3 = O_2 + O\text{I}({}^1D_2) + N_2 + \epsilon'' \qquad (18)$$

might have a relatively large probability.

As mentioned by Vegard [1379], the direct excitation of the ${}^1D_2$-state from ozone (equation 14) without passage through the ${}^1S_0$-state might account for the large variations of relative intensity of the red and the strong green auroral lines and the enhancement of the red lines, which as we shall see produce the red-colored aurorae of type A.

The explanation here given for the peculiar intensity-distribution of the lines of oxygen, which McLennan's interpretation of the green line would involve, is supported by the fact that the green line of oxygen, as shown by Kaplan [821], can be excited by active nitrogen.

The excitation-process which leads to the emission of the green OI-line and the red OI-triplet has been dealt with in a number of papers recently published by Vegard [1379, 1380-B, 1110]. It is shown that if the ${}^1D_2$-state is reached only through the transition, ${}^1S_0 \rightarrow {}^1D_2$, resulting in the emission of the green line, then the intensity of the red line 6300, relative to the green one, cannot be greater than a quantity (κ) which is about

0.5. In certain cases of red or sunlit aurora the red line may be very strong, and quantitative measurements showed in certain cases that the red line can be more than twice as strong as the green one. *This means that excitation-processes must be operating in the auroral region bringing the OI-atom directly to the $^1D_2$-state.* Such an excitation-process is given by equation (18) and, after having discussed various possibilities, Vegard finds that the excitation of ozone with nitrogen in an activated state, for example, the $(A^3\Sigma)$-state, is the one which best explains the type and the variations found for the auroral spectrum.

Assuming that the O_2-molecule is not left in the normal state, but in the $(A^1\Sigma\bar{u})$-state, we may explain that the process does not give the $OI(^1S_0)$-state and that the probability of its occurrence is increased by resonance.

A number of weak lines are referred to *O*I- and *O*II-lines or lines emitted from neutral or ionized oxygen atoms. The correctness of this interpretation was supported by spectrograms obtained by Vegard and Tönsberg [1380-*B*, 1383-*A*] with a spectrograph of large dispersion, where two lines, 4415.1 and 4368.2, appeared quite distinctly. On account of the large dispersion the lines were measured with an error less than one Ångstrom, and they were found to coincide with pronounced *O*I- and *O*II-lines. It is very remarkable that the intensity of the *O*-lines increases with the sunspot-frequency. This indicates that the *concentration of oxygen atoms as well as that of ozone molecules varies in a similar way as the sunspot-frequency.*

(4) INTENSITY-DISTRIBUTION WITHIN THE AURORAL SPECTRUM

The frequent changes of color of the aurorae correspond to variations of the intensity-distribution within the auroral spectrum. In spite of these variations, which will be dealt with in a later Section, we speak of a typical, or a kind of average, distribution, which corresponds to that obtained on spectrograms taken with very long exposures. These spectra integrate the luminescence from a great variety of auroral forms and displays during weeks or even months.

Quantitative measurements of the relative energy of some of the more prominent lines appearing in such spectra were made by Vegard [848, 1374]. The results so far published are restricted to the green line and the bands of the negative and second positive group of nitrogen. But in the region of these bands also the intensity of other lines, which appear in between, can be fairly accurately estimated. The relative intensities, *I*, which may be regarded as fairly accurately measured or estimated, are given in the second column of Table 13.

Investigations with the object of improving these measurements and extending them to the region of long waves have been continued at the

Auroral Observatory by Vegard and Tönsberg. The typical intensity-distribution within the auroral spectrum is illustrated in Figure 18. In the region of long waves, the intensities are very variable and the measurements in this region can give only a rough impression of the intensity-distribution.

The intensity-distribution of the bands within either the negative group or the second positive group of nitrogen is found to be of the type to be expected from the Franck-Condon theory of intensities of vibrational band-systems.

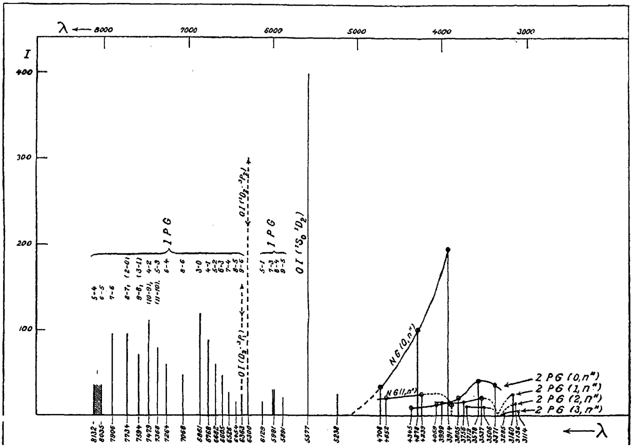


FIG. 18.—Typical energy-distribution within auroral spectrum.

VI. SOME REMARKABLE VARIATIONS OF INTENSITY WITHIN THE AURORAL SPECTRUM

(1) SPECTRAL CHANGES PRODUCING RED AURORAE

The typical intensity-distribution derived from spectrograms of long exposure shows one most remarkable variation, which is due to the relative enhancement of the red lines near 6300. Spectra on panchromatic plates, obtained by Vegard in 1923, showed only faintly the red line near 6300. In 1926, however, the aurorae very often had a dark-red color, which was not confined to the part near the bottom edge but extended to the very top of the streamers. Vegard obtained auroral spectrograms of such aurorae at Oslo and studied the spectrum spectroscopically. The spectrum in red, which is usually not seen, now consisted of what in the small spectroscope appeared to be a single line which gave the impression of being as strong as the strong green line. This result was confirmed by the spectrograms in which a somewhat broad and very strong red line was observed. The wave-length of this line was found to be 6309, and somewhat larger from some plates.

Later auroral spectrograms taken with the same spectrograph and a very narrow slit showed that the line consisted of the two red lines previously mentioned, namely, 6302 and 6367—the lines which form the two strongest components of the *O*I-triplet. At the same time, Vegard's observations at Tromsö with panchromatic plates gave the same enhanced red lines [compare references 1366 and 1374]. The frequent occurrence of red aurorae and the enhancement of the red lines continued during the whole year.

As stated in previous papers by Vegard [1374], these results indicate that the probability for red aurorae of this type caused by the enhancement of the lines near 6300 is due to changes of a universal nature taking place at the same time near the auroral zone at Tromsö and at the lower latitude of Oslo *and that the enhancement of these red lines follows the sunspot-cycle.* The latter statement has been confirmed by the work at Tromsö, where during the few years near a sunspot-minimum these red lines were very weak, after which the red triplet became stronger as the present sunspot-maximum was approached.

If this *O*I-triplet is excited indirectly through collisions of the second kind with nitrogen molecules, the enhancement must correspond to some change which takes place in the composition or physical state of the upper atmosphere. If the enhanced lines were excited directly through collisions with the solar electric rays, the intensity-variation of the red lines might also be due to some change taking place in the solar electric rays. This variation could not be a variation of velocity, because the red aurorae of this type, *A*, appear at the ordinary altitude, but it would have to be a change in the composition of the solar electric rays, which then would have to be regarded as being composed of a mixture of electrons and positive ions.

On the basis of the interpretation previously given for the red lines, Vegard [1379] suggested as a possible explanation that the atom of oxygen may be excited to the $^1D_2$-state through the action of N_2^4 on ozone in accordance with equation (14). If then the green line was mainly excited by a process as expressed by equation (16), the relative intensity of the red triplet would increase with increase of concentration of ozone. Such an explanation is supported by the fact that the ozone concentration, as well as the relative intensity of these red auroral lines, seems to follow the sunspot-frequency.

This view regarding the enhancement of the red *O*I-triplet was strongly supported by the discovery of Vegard and Tönsberg [1383-*C*, 1383-*D*] that the red *O*I-triplet (and usually also the bands of the first positive group) were largely enhanced when the auroral luminescence was emitted from an atmosphere exposed to sunlight. Vegard showed [1110] that this effect cannot be due to a direct influence of sunlight on the emission-process but must be due to some change in composition or state of the atmosphere produced by the Sun's radiation, and it is very likely that this change consists in the formation of ozone.

This explanation of the variation of the *O*I-triplet is also supported by the fact already mentioned that certain *O*II-lines appear enhanced during periods near sunspot-maxima, for we may expect that a high O_3-concentration is accompanied with a large concentration of atomic oxygen.

Besides the types of red aurorae here described, there is a second one which was observed in 1913 by Vegard at Bossekop and by Krogness at Haldde and was discussed by Vegard [845, 1359, 1379]. This aurora had the form of a long drapery-shaped arc, with color of the upper part of the streamers ordinary greenish-yellow and of the lower part intense red. Vegard [845, 1379] called this red aurora "type *B*" and explained the red color as due to the enhancement of red bands belonging to the first positive group of nitrogen. The intensity of these bands is found to increase with decrease of velocity of the cathode rays and with increase of pressure; in this way, he accounted for the fact that the red color is restricted to the lower limit where the average velocity is smallest and the pressure is greatest. To explain why these red lower limits occur only infrequently, Vegard assumed that they are cases of aurora reaching down to very low altitudes. Later a similar arc was observed at the Auroral Observatory of Tromsö and its height was measured by Harang and Bauer [815]; they found, in accordance with Vegard's suggestion, that the lower limit had the exceptionally small value of 65 to 70 km. This means that the relative enhancement of the bands of the first positive group first becomes very marked when the pressure increases above, say 0.01 mm of mercury, corresponding to an altitude of about 78 km.

The aurorae of type *B* have a tendency to occur near sunspot-minimum, and the measurements of height by Harang and Bauer suggested that the maximum energy obtained by the solar electric rays is larger at sunspot-minimum than at sunspot-maximum. From his theory of the solar corona, Vegard [1379] suggested that the larger maximum energy of solar electric rays at sunspot-minimum is closely related to the fact that the coronal streamers have their largest extension during sunspot-minimum because, according to his theory, the length of the streamers should increase with the velocity of the cathode rays emitted by the Sun. Quantitative intensity-measurements by Vegard and Tönsberg [1383-*D*] for spectra obtained from aurorae with a red bottom-edge have shown that the first positive group in fact appeared considerably enhanced in these spectra. Recently Vegard [1380-*B*, 1380-*C*] showed that *the intensity of the first positive group increased with decrease of altitude.* Only when the aurorae come down to very low altitudes is the enhancement of the first positive group sufficient to give the aurora a red bottom-edge.

(2) ALTITUDE-EFFECTS

As already mentioned, it is of great importance to determine whether the auroral spectrum changes with altitude and especially to learn how far the intensity of the strong green line, compared with that of the bands of nitrogen, may vary as we pass toward greater heights. Investigations on the variation of the auroral spectrum with altitude were undertaken by Vegard [847, 848, 1374] in 1923. Using small glass spectrographs (Fig. 13-*A*), he obtained on the same plate one spectrogram corresponding to the upper and one corresponding to the lower limit of the auroral streamers. Care was taken that both spectra had about the same photographic density, which was on the steep part of the curve giving the relation between density and exposure. A lens was placed in front of the slit in such a way that the picture it formed of an aurora fell on the slit. Thus only light from the desired part of an auroral streamer entered the instrument. An intensity-scale was photographed on the same plate. Two successful plates fulfilling the condition of accurate photometry were obtained, one on March 11 and one on March 12, 1923. The relative intensities were measured by a Moll registering photometer. Description of the observations and measurements are given in the papers referred to.

The following two typical altitude-effects were discovered: (1) The intensity of the green auroral line (*b*) relative to one of the negative bands of nitrogen (*n*) decreased very markedly with increasing altitude; (2) the intensity of certain weak lines in the region 4300 to 4600 Ångstroms (α), relative to that of the negative bands of nitrogen (n), was found to increase with increasing altitude.

Let *A* and *B* denote the two *spectra* to be compared, and *b* and *n* the *lines* to be compared. The photometric measurements then give us means of determining a quantity

$$D(bn) = (I_b/I_n)_A : (I_b/I_n)_B \qquad (19)$$

which characterizes the intensity-variation. If D is equal to 1, there is no change of relative intensity; $(1 - D)$ therefore gives a measure of the variation [compare reference 1374]. Let A and B correspond to upper and lower limits, respectively. Comparing the auroral line with one of the negative bands of nitrogen, the two spectra obtained March 11 give $D(bn) = 0.707$ and the two spectra obtained March 12 give $D(bn) = 0.700$. For the weak lines which are enhanced with altitude we get, on an average, $D(n\alpha) = 0.84$.

From the measurements of the height and length of streamers of this type of aurora, Vegard estimates that this variation of relative intensity corresponds to a difference of altitude of about 50 km. The spectrum of the lower limit corresponds to an average height of, say, 110 km and that of the upper limit to about 160 km.

Some interesting studies of the variation with altitude of the spectral composition of the auroral luminescence were made at the Auroral Observatory at Tromsö by Harang [814]. He studied the variation of light-intensity in various spectral regions, by taking simultaneous auroral photographs with two cameras and with differently colored filters in front of each lens. Comparing photographs taken on orthochromatic plates through yellow and through blue filters, he found that the intensity for the latter decreases less rapidly upward than that for the former. Harang thus compared the yellow-green luminescence consisting mostly of the green line with the *total* emission in blue and violet. Thus his experiments are not exactly comparable with those of Vegard which dealt with individual spectral lines. Vegard's measurements of the intensity-distribution within the auroral spectrum show that the negative bands are very predominant in the region of short waves; further, his second altitude-effect shows that certain lines in the blue part are enhanced with increasing altitude relative to the negative bands of nitrogen. As a result Harang, who compared the total emission in blue and violet, ought to have found an effect larger than that found by Vegard for the change of the intensity of the green line relative to that of the negative bands of nitrogen only. In fact, Harang found a somewhat larger effect, in agreement with Vegard's measurements.

In 1929 Störmer [836] and Moxnes obtained a spectrogram from very long auroral rays exposed to sunlight. Störmer compared this spectrum with that of another plate from an aurora of the ordinary height and concluded that the green line is relatively much weaker for sunlit aurorae. As indicated by Vegard [849], the two spectrograms were not comparable because they were taken on different plates and differed too much with regard to photographic density to justify a comparison with regard to variation of intensity-distribution. On the other hand, spectra like those taken by Störmer and Moxnes—when comparable—should show a very large effect in the direction mentioned. The two spectra correspond to a difference of height of 200 to 300 km and, therefore, the relative intensity of the green line, because of the altitude-effect, should be very much smaller on the spectrograms from the sunlit rays.

Thus the spectra obtained by Störmer from long sunlit rays give no information as to the possible influence of sunlight on the composition of the auroral luminescence.

In 1935 and the following years, Vegard and Tönsberg obtained on panchromatic plates spectrograms from arcs and bands exposed to sunlight. In this case the altitude-effect is very small because, as shown by Harang, the sunlight has only a fairly small effect in increasing the altitude of an auroral arc.

Under these conditions it appeared [1383-*C*, 1383-*D*] that the intensity of the green line, relative to that of the negative bands, was only slightly smaller for sunlit aurorae as compared with aurorae of the same type subject to night conditions. Thus the large change indicated by Störmer's spectrograms was mainly due to altitude-effect.

As already mentioned, it was found that the red *O*I-triplet and usually the red bands of the first positive group were largely enhanced in an atmosphere exposed to sunlight. During an auroral display which occurred October 16, 1936, Vegard—observing at Oslo—found that the intensity of the red triplet is considerably enhanced as we pass upward along the ray-streamers. As a consequence, the upper part of the rays appeared red, while the lower part had the ordinary greenish color [1380-*A*]. This result was confirmed by later observations and quantitative intensity-measurements [1110].

In 1937 Störmer published some spectrograms [1352-*A*] from long auroral rays exposed to sunlight and found that the red *O*I-triplet appeared with unusual intensity. In this case the enhancement is due to three different effects: (1) The sunlight-effect; (2) the altitude-effect; and (3) the enhancement accompanying the increase of solar activity, which is responsible for red aurora of type *A*.

Currie and Edwards [808], who have taken a number of spectrograms for the study of the presence or absence of aurora, mention that some red lines usually appear relatively stronger near sunset and dawn. As the conditions are not specified, the effect is open to numerous possible explanations, which the authors discuss in their paper.

Kosirev and Eropkin [1321-*A*] have obtained a spectrogram from a sunlit atmosphere, and find a relative weakening of the green line. The effect, however, has nothing to do with the enhancement of the red triplet discovered by Vegard and Tönsberg. The change they observe is probably due to the altitude-effect described by Vegard in 1923.

(3) VARIATION OF THE SPECTRUM WITH THE TYPE OF THE AURORAE

Vegard and his collaborators [1374, 1381, 1383-*D*] have undertaken extensive investigations on the possible variations of the spectral composition with auroral type. Among the results obtained we may mention the following:

(*a*) The intensity of the green line relative to that of the negative nitrogen bands is smaller for diffuse forms like gray and pulsating surfaces than for sharper forms like bands and draperies.

(*b*) The intensity of the red triplet and the red bands of the first positive group is greater for diffuse than for the more distinct forms.

(*c*) For some diffuse aurorae some lines or bands in the blue part (4700 to 4200) may become quite pronounced. In some cases the number of weak lines is so large that they cannot be separated by the instruments used, and they form nearly a continuous band. Such an effect of that type is illustrated by spectrograms Nos. 5 and 6 of Fig. 15, corresponding to distinct forms and more diffuse aurorae, respectively.

The variations are similar to the changes with altitude; this would suggest the explanation that the diffuse aurorae, on the average, were situated at an altitude of, say 150 km, while most light from those with radiant structure came from a height of 105 km. However, the measurements of height [compare section I-7] show that the diffuse forms, on the average, appear at the same altitude as the arcs and drapery-shaped arcs. Therefore, it seems that we are dealing with a true "type-effect," which exists independent of the altitude-effect and which corresponds to variations regarding the excitation-process. The explanation naturally suggests itself that the type-effect is due to a change in the composition of the electric rays. We cannot account for it through changes in the composition and state of the atmosphere because the two types may follow each other in rapid succession.

(4) REMARKS REGARDING THE INTERPRETATION OF THE SPECTRAL VARIATIONS

In some papers recently published, Vegard has given a general classification of the most important spectral variations with which we have to deal in the auroral studies, and he discusses a number of possible ways in which the observed effects may be explained [1110, 1380-*B*].

A complete theory of the spectral variations should have to account for and coordinate all the observed facts. First of all we must take into account that the auroral luminescence is primarily excited by the electric rays which enter the atmosphere. From the type of spectrum and from the intensity-distribution and altitude of the aurora, Vegard finds that the luminescence is mainly produced by electron-rays with velocities corresponding to some thousand electron-volts.

This result accounts for the relative intensity of the nitrogen bands which appear in the auroral spectrum and shows that the large strength of the green oxygen line (${}^1S_0 \rightarrow {}^1D_2$), and the triplet, $OII({}^1D_2 \rightarrow {}^3P_{012})$, cannot be merely due to the primary excitation-process, but that secondary processes like those given by equations (16) and (18) will have to play an important part. Assuming that the negative nitrogen bands result from the collision between N_2-molecules and the primary rays and that the green line is excited according to equation (16), Vegard finds that the intensity of the green line, I_g, relative to that of the negative bands, I_n, may be expressed by an equation of the form

$$I_g/I_n = \kappa[\epsilon_s N^2 O_2/q(v) N_2] \tag{20}$$

N, N_2, and O_2 represent the concentration of atomic nitrogen, nitrogen molecules, and O_2-molecules; $q(v)$ is the excitation-function of the negative nitrogen bands; ϵ_s is the fraction of the O-atoms brought to the ${}^1S_0$-state which performs the transition, $({}^1S_0 \rightarrow {}^1D_2)$.

The observed altitude-effect should then mean that the expression to the left decreases with altitude and, as (O_2/N_2) is nearly independent of altitude, the quantity $[\epsilon_s N^2/q(v)]$, must diminish with increasing altitude and this is likely to be the case.

Independent of any hypotheses regarding the nature of the excitation-process, the intensity, I_r, of the strongest component of the red triplet, relative to that of the green line, I_g, can be expressed by the equation [1380-*B*, 1110]

$$I_r/I_g = \kappa\epsilon_d(1 + \Delta_d/\epsilon_s n_s) \tag{21a}$$

where $\kappa = \lambda_g/[\lambda_r(1 + \alpha + \beta)]$ and α and β are the relative intensities of the components, $OI({}^1D_2 \rightarrow {}^3P_1)$ and $OI({}^1D_2 \rightarrow {}^3P_0)$. ϵ_d is the fraction of those O-atoms brought into the ${}^1D_2$-state which perform the transition to the ${}^3P_{012}$-states. ϵ_s is the corresponding fraction for the ${}^1S_0$-state. n_s is the number of O-atoms brought to the ${}^1S_0$-state in unit-time. Δ_d is the number of O-atoms brought to the ${}^1D_2$-state in unit-time directly without passage through the ${}^1S_0$-state.

The quantities, ϵ_s and ϵ_d, are functions of pressure in such a way that $\epsilon = 0$ for all pressures above a certain small value; this means that ϵ_s and ϵ_d are zero below certain altitudes, H_s and H_d, characteristic for the two metastable states. The lifetime of the ${}^1S_0$-state is about 0.5 sec, and that of the ${}^1D_2$-state is about 100 sec. This means that the green line and the red triplet can be emitted only from the very highest atmospheric strata and that H_s is considerably smaller than H_d. If, for example, H_s is equal to 70 km, H_d is about 100 km. The green line is emitted in this interval between H_s and H_d, but not the red triplet.

As the factor, ϵ_d, of equation (21*a*) increases upward, the equation gives without further hypothesis an explanation of the enhancement of the red line with altitude. In the cases when the red triplet appears very strong, its intensity is mainly determined by the quantity, Δ_d, and this quantity also essentially influences the altitude-effect. If the states,

$OI(^1S_0)$ and $OI(^1D_2)$, are excited according to the equations (16) and (18) respectively, we obtain

$$\Delta_d/\epsilon_s n_s = \kappa(N_2O_3/\epsilon_s N^2O_2) \qquad (21b)$$

The altitude-effect of the red line thus ought to result partly from the increase of Δ_d and partly from the increase of the left part of equation (21*a*) with increasing altitude [compare references 1110, 1380-*B*].

It appears that the interpretation of the variations of the spectral intensity-distribution is very complicated. Even when we base the interpretation on the excitation-process, for example, (16) and (18), a calculation of the effects meets with considerable difficulties.

VII. AURORAL SPECTRUM AND THE UPPER ATMOSPHERE

(1) Composition of the upper atmosphere

The auroral luminescence is dominated by the band-spectra of nitrogen and the strong green line which originates from oxygen. We find no evidence of a layer of the light gases, hydrogen and helium. The existence of a layer of light gases at the top of the atmosphere is a necessary consequence of the assumption that above a certain altitude the translatory and turbulent motion of matter is small compared with the velocity of diffusion and that an ideal equilibrium of gas-mixtures in a gravitational field is established. This means that the pressure of each gas varies upward as though the others were not present. The absence of the hydrogen-helium layers shows that no such ideal equilibrium is established.

Apart from the presence of ozone and certain fluctuations in the composition of the upper atmosphere from incoming radiant matter, we may regard the composition of the atmosphere as independent of altitude. This conclusion is confirmed by observations of the luminous night clouds. Very accurate measurements of altitude and velocity of these clouds were made by Störmer [1352], who found an average altitude of 81.4 km and velocities varying between 44 and 55 meters per sec.

In the lower part of the auroral region the atmosphere is in rapid motion, which no doubt is partly turbulent, and this will prevent the establishment of an ideal equilibrium. The formation of an ideal equilibrium is disturbed also by the formation of ozone in the upper layers through the effect of ultraviolet light. This production of ozone, which is strong on the dayside and very small on the nightside of the Earth, will introduce a periodic variation in the average molecular weight of the atmospheric gases which, according to the equation for the variation of pressure with altitude, will disturb the equilibrium in a gravitational field. The equilibrium may be disturbed also to some extent by radiant matter coming from space, mainly from the Sun. Thus, for example, the formation of the luminous night clouds may be due to proton rays which enter the atmosphere and combine with oxygen—perhaps in the form of ozone—which again condenses to water at an altitude of 80 km, where the pressure is of the same order of magnitude as the vapor-pressure of water at the low temperature existing at this altitude [1379]. As seen from Table 11, the pressure at an altitude of 80 km is about 0.004 mm of mercury. That water-vapor may condense at this altitude, the vapor-pressure should be smaller than 0.004 mm of mercury and the temperature should be lower than −63°C. If the luminous night clouds consist of water in the form of ice in any degree, the temperature at an altitude of 80 km should be below −63°C or 210°K.

(2) AN UPPER LIMIT OF THE TEMPERATURE OF THE AURORAL REGION DETERMINED FROM THE ROTATIONAL NITROGEN BANDS

When a gas composed of molecules is in thermodynamic equilibrium, each molecule will have an average energy of rotation proportional to the absolute temperature. If we regard the instantaneous state, the rotational energy will be distributed to the various molecules according to the Maxwell distribution-law.

According to the quantum theory of band-spectra, the molecules can exist only in certain definite energy-states; when a molecule is excited to an abnormally high electric state, the establishment of normal conditions is accompanied by the emission of what is called a band-system. Through the excitation- and recombination-process, the atoms in the molecules reach various vibrational states, both before and after the "electronic jump" has taken place. The light corresponding to the same electronic jump and the same vibrational states forms a so-called rotational series. The lines within this series correspond to transitions between states which differ only with regard to the rotational energy.

From the theory of band-spectra, we know that the rotational quantum number, j, during the emission-process, changes only by one unit or in some cases may be left unchanged. Let the rotational quantum number at the upper and lower level be J' and J''. Then all transitions for which $(J' - J'') = -1$ give a collection of lines called the P-branch; $(J' - J'') = +1$ gives the R-branch; and $(J' - J'') = 0$ gives the Q-branch. The rotational energy increases with the rotational quantum number, and a sequence of lines forming an R-branch corresponds to increasing rotational quantum number of the molecule in the excited state. The intensity-distribution of the lines within the branch must depend on the distribution of energy of the molecules which are engaged in the emission of the band. If the excitation-process did not disturb the rotational energy, the distribution of energy within a branch of a rotational band would be a function of temperature.

Combining the quantum theory of the rotational band-spectra with the Maxwell distribution-law of rotational energy, we find for a certain type of molecule how the intensity-distribution within the branch depends on temperature. In other words, we know how the intensity of a line depends on the rotational quantum number and the temperature.

In the case of the bands belonging to the negative group of nitrogen, the intensity-distribution within the R-branch is given by the equation,

$$\left.\begin{aligned} I &= cj \exp\left[-\kappa(j+\tfrac{1}{2})^2\right] \\ \text{or} \qquad \log \text{nat}\ (I/j) &= -\kappa(j+\tfrac{1}{2})^2 \end{aligned}\right\} \tag{22a}$$

where j is the rotational quantum number corresponding to the upper level and

$$\kappa = h^2/8\pi^2JkT \tag{22b}$$

where h is Planck's constant $= 6.55 \times 10^{-27}$, J is the moment of inertia of the N_2^+-ion in the upper state $= 13.4 \times 10^{-40}$, k is Boltzmann's constant $= 1.37 \times 10^{-16}$, and T is the absolute temperature. If then we can measure the intensity-distribution for bands of known quantum number, we can find the temperatures.

Now suppose we have a gas which in its non-luminous state is in thermodynamic equilibrium at a temperature, T. If we now excite the gas to luminescence, the excitation-process, to a certain extent, will usually increase the rotational and translatory energy of the molecules. The excitation-process will disturb the thermodynamic equilibrium, the result of which may be an increase of the temperature of the gas in the luminous region to a value, T_1; but even this temperature may not be the effective temperature determining the intensity-distribution within a rotational band. The excited molecules may receive rotational energy through the excitation-agency and the molecules actually engaged in the emission-process may have an average rotational energy considerably larger than that of the surrounding gas. If the time between excitation and re-emission is small compared with the time between two collisions—the case at sufficiently low pressures and temperatures—the distribution of energy on the various excited molecules may not even follow the Maxwell distribution-law. Therefore, it is not excluded that band-spectra excited directly by electric rays at low pressure may give an intensity-distribution within the rotational bands, which is not in accord with the law derived from the Maxwell distribution of energy, for example, that which is expressed by equations (22). But even if the intensity-distribution follows this law and we determine the corresponding temperature, T_2, this temperature will be larger than both T and T_1. The difference between the temperature derived from the rotational bands and the temperature, T, of the gas before excitation will depend on the type of exciting agency, its intensity, the pressure and temperature of the gas, and perhaps also on the dimensions of the receiver containing the gas. For application to the auroral problem, the most important type of exciting agency is that of electric rays passing through the gas.

To investigate the influence of electric rays on the intensity-distribution within the rotational bands, Vegard and his collaborators [1307, 1374] made some experiments by which electric rays were made to pass through a tube which contained nitrogen at low pressure and which could be cooled by suitable liquids—for example, down to the temperature of liquid air.

Some preliminary experiments mentioned in previous publications have shown that cathode rays of moderate density by their impact affect, only to a small extent, the rotational energy of the molecules. The spectra were obtained with a dispersion which was too small for the separation of the individual lines; but at least it could be shown that cooling with liquid air gave a very large effect on the extension of the R-branch and on the position of the maximum of intensity. This relatively large temperature-effect shows that the rotational energy directly produced by collisions with fairly swift cathode rays is small compared with that which the molecules possess at the temperature of an ordinary room, or that the difference $(T_2 - T)$ is very small compared with $T_0 = 273°K$. A fairly accurate determination of the temperature from the position of the maxima and the intensity-distribution within the R-branch gave values for T_2 which were not far from the temperature, T, of the receiver.

Some preliminary experiments with canal rays have shown that the impact of canal rays has a considerably larger effect on the rotational energy than cathode rays. Systematic and quantitative experiments along these lines were made at the Physical Institute at Oslo.

From these considerations we may say that the intensity-distribution within the rotational bands obtained by excitation with electric rays at low pressure is essentially determined by the temperature of the gas (or the temperature of the receiver containing it). The temperature found from the band-spectra is bound to be somewhat larger than the temperature of the receiver or the temperature possessed by the gas without excitation. *Thus the temperature derived from the intensity-distribution of rotational bands gives an upper limit to the temperature existing before excitation and, for the case of excitation with swift cathode rays at low pressure, the temperature should not be much increased through the excitation-process.*

Each of the auroral bands belonging to the negative and first and second positive groups of nitrogen forms such a rotational band composed of a series of individual lines which, for the dispersion used, are too close to appear separated. For the negative and second positive groups, the P-branch forms a fairly sharp head separated from the R-branch which extends toward shorter waves. The extension of the *R*-branch and the position of its maximum will give us a means of determining the apparent temperature of the emitting centers. Because of the great intensity, the negative bands of nitrogen were first utilized for this purpose.

During 1922–26 several auroral spectrograms were obtained with fairly large dispersion. As the strongest band, 3914 Ångstroms, was considerably absorbed through the large Rutherford prism, the band 4278 Ångstroms was most suitable for measurements (compare No. 7, *c*, and *d* of Fig. 15). Each photographic plate was provided with an intensity-scale. The individual rotational lines are not separated and therefore we cannot rely on absolute measurements by means of the formulas (22).

The intensity-distribution of a continuous *R*-band formed by overlapping lines may not be the same as that found for individual separated lines, since the lines are not equidistant. Vegard [1373, 1374] therefore adopted a method by which the *R*-branch of the 4278-band from the auroral spectrum was compared with the spectrograms of about the same dispersion, obtained by experiments in the laboratory at known temperatures, the light being excited under similar conditions as those existing in the auroral region. The luminescence was produced by cathode rays which were shot into a tube which could be given any temperature desired. *This method is independent of the particular law which determines the relation between intensity-distribution and temperature*, and it is sufficient to know that the development of the *R*-branch as a whole is a function of temperature which is determined by direct experiment.

Spectrograms of the 4278-band at ordinary temperature in a room and at the temperature of liquid air [1307] were compared with the same band from auroral spectrograms; from this direct comparison and interpolation, Vegard [1373, 1374] found a temperature of −27°C. To estimate how far the band-spectra were influenced by the excitation-process, the temperatures were also determined from the theoretical formulas (22) for the intensity-distribution within the *R*-branch. Although these determinations were not very accurate, they showed that the rotational energy which the emitting molecules derive directly from the impacts with cathode rays is small and probably smaller than the absolute temperature of the liquid air. An "absolute" determination of the temperature of the auroral region by the intensity-distribution within the *R*-branch gave a temperature of −33°C. This first "absolute" determination cannot claim any great accuracy but gives the right order of magnitude. For the reasons mentioned, the relative determinations ought to give the most accurate results.

These measurements of temperature were continued by Vegard and his collaborators, E. Tönsberg, S. Stensholt, and Th. Ringdal. To evaluate the temperature from spectrograms of moderate dispersion a systematic study was made, in the laboratory at Oslo, of the influence of temperature on the R-branch. From the same source of light which is produced by shooting electric rays of various sorts into a tube of known temperature, spectrograms were taken with spectrographs of different dispersion. The "effective" rotational temperature of the emitting centers was determined by means of the bands where the individual lines are separated. The temperatures thus found were then used to get a true scale of temperature for bands obtained with such small dispersion that they appear to be continuous.

The determinations made of temperature show that the temperature of the auroral region is fairly low and should not exceed −30°C at night. We must, however, expect to find considerable fluctuations of the temperature derived from the distribution of rotational energy of the emitting molecules.

The mean temperature derived from the measurements from 11 different spectrograms obtained during the period from 1923–1938 is $-44\overset{\circ}{.}2$C or $228\overset{\circ}{.}8$K [1383, 1383-B].

Experiments in the laboratory indicate that when the density of the electric radiation is small—actually the case in the auroral region—the apparent temperature measured from the rotational bands is not much higher than the temperature of the surrounding gas or of the temperature existing in the non-luminous regions at the same altitude. As the temperature derived from the rotational bands should give an upper limit of the temperature in the auroral region without luminescence, our result is not in conflict with the upper limit of temperature of −63°C, estimated from the appearance of luminous night clouds at an altitude of 80 km.

S. Rosseland and G. Steensholt [1335] attempted to determine the temperature of the auroral region by means of the intensity-distribution within the *vibrational* bands. However, the following simple considerations show that their method is not applicable to luminescence phenomena like the aurorae. The energy-quanta of the vibrational energy are so large that the energy-distribution of the vibrational bands will not be essentially influenced by temperatures of the order of magnitude here considered. The auroral light is a luminescence and not a thermal radiation, and when the luminescence is due to excitation at low temperature because of electric rays, the intensity-distribution is mainly determined by the Franck-Condon principle and may also depend on the excitation-process. Nitrogen at low temperature, or even in the solid state, emits vibrational band-systems for which the application of the method of Rosseland and Steensholt would give temperatures of several thousand degrees, while the actual temperature may be that of liquid helium. The inapplicability of the method is also shown by the fact that it leads to temperatures of the auroral region of several thousand degrees, while the rotational bands fix an upper limit below 0°C.

(3) ELECTRICAL STATE OF THE UPPER ATMOSPHERE AND THE TERRESTRIAL CORONA

From the discovery in 1923 of the spectral altitude-effect, Vegard showed that some very important conclusions could be drawn regarding the physical state of the upper atmosphere [847]. Compared with the green auroral line, the relative intensity of the nitrogen band-spectrum was found to increase toward larger altitudes. On the other hand, the auroral line can be followed spectroscopically to altitudes of several hundred km. The nitrogen bands of the auroral spectrum thus become more and more dominating as we pass upward, and nitrogen forms a predominant component of the atmosphere up to its very limit.

Investigations on the distribution of luminescence along the streamers and on the determination of their altitudes had shown that auroral streamers, especially in the form of isolated rays, might maintain a fairly constant intensity per unit-length up to hundreds of km. Near the auroral zone, the maximum altitude of rays was found to be about 300 km. Störmer [835, 836] found that at lower latitudes the rays may extend as high as 800 km or even more.

If the atmosphere up to its limit could be treated as a neutral gas in the Earth's gravitational field, the pressure of nitrogen should vary, approximately at least, in the way given in Table 11. The rate of change of pressure within the auroral region given in Table 11 corresponds to a temperature which is of the order found from the rotational band-spectra and the luminous night clouds. This means that for each 15 km we pass upward, the pressure is reduced by one-tenth. A very usual auroral streamer extends from 100 to, say 160 km, but even for such a fairly short streamer the pressure and density at its lower end should be 10,000 times that of the upper end. If the ray reaches an altitude of 250 km, the pressure at the lower limit should be 10,000 million times as large as at the top, although the light-intensity per unit-length may be practically constant all the way. The theoretical distribution of luminescence due to a nitrogen distribution following the ordinary gas is shown by curve I of Figure 9 for α rays, and by curve II of Figure 10 for electron rays. In both cases the rays are supposed to reach an altitude of 100 km. In both cases we see that the intensity falls off very rapidly when we pass from the maximum toward higher altitudes.

From Section III-3 we saw that the distribution of intensity along the streamers may be altered in two ways: (1) The angles which the rays form with the magnetic lines of force (or the angular distribution-curve, Fig. 11) may be changed; (2) if the electric rays are not homogeneous, but composed of a mixture of rays differing largely with regard to penetrating power, changes of light-distribution would result from a change of composition.

Thus we may account for variations within reasonable limits but we cannot assume that the intensity can be increased in this way near the upper limit in the ratio of 10^{20} to 1, which would be necessary to explain streamers reaching altitudes of 400 km. For rays reaching 700 km the intensity at the upper edge, because of one of the two causes mentioned, should be increased in the proportion of 10^{40} to 1. The only escape from the difficulty is to assume that the decrease of density of nitrogen upward follows a law quite different from that of a neutral gas in a gravitational field.

As a radiation-pressure cannot be considered, Vegard [847] concluded that in the auroral region the nitrogen in an electrically charged state is carried toward higher altitudes through the effect of an electric field—a state of things which results from the action of a radiation from the Sun of short wave-length of the type of soft X rays. Through the action of these solar rays—to a small extent also through the cosmic radiation—the upper atmospheric layer is ionized and electrons are driven out from the molecules with a velocity, v, given by the Einstein equation

$$mc^2\{[1/\sqrt{1-(v/c)^2}]-1\}=h\nu-W \tag{23}$$

where ν is the frequency, m is the mass of an electron, and W is the energy necessary to remove the electron from the molecule (or atom). The slow-moving electrons will soon be absorbed but, as the velocity increases, the distance they travel before absorption increases; this distance will be much greater in the upward direction than in the opposite. This asymmetry in the absorption of the electrons will produce an electric separation. Above a certain altitude the solar rays of shortest wave-length may produce photoelectrons with sufficient energy to penetrate the whole atmospheric layer above the height considered. As a result, the atmosphere above a certain altitude will be left in a highly ionized state and with a surplus of positive ions.

The photoelectrons moving in an upward direction will be retarded by the electric field set up by the electric separation and will stop at an altitude, h, given by the equation

$$mc^2\{[1/\sqrt{1-(v/c)^2}]-1\}=e(V_s-V_h)+a \tag{24}$$

where V_s is the potential at the point where the electron is liberated, V_h is the potential where the electron stops, and a is the energy expended on account of absorption. The value $(V_s - V_h)$ increases with increasing frequency and the maximum value should be determined by the highest frequency of the radiation entering the atmosphere. As a result of this retardation, electrons will accumulate within a certain interval of height above the positively charged layer. As long as the solar rays are acting, this separation into a lower layer with positive and a higher layer with negative volume-charge will be maintained. For volume-elements with linear dimensions, which are large compared with the mean free-paths of the positive ions, the variation of pressure is determined by the equation

$$dp = (-g\rho + \sigma F)dh \tag{25}$$

where σ is the electric volume-density and F is the intensity of the electric field.

The problem of determining the distribution of an electrically charged gas under the combined action of an electric and gravitational field was treated by Vegard [847] in 1923 and later by Rosseland [1334] and by Hulburt [406]. A complete solution is possible only by introducing certain additional hypotheses, for example, by regarding the distribution of frequencies of the active radiation and the relation between ionization and density; but as the resulting surplus charge and the distribution of matter are interlinked in a most complicated way an exact solution is hopelessly complicated. The complication is also increased because of the magnetic and electric fields which influence the motion of ions and electrons.

Although we cannot as yet give any exact solution of the problem, certain consequences can be drawn regarding the state of the upper atmosphere resulting from the photoelectric action of rays of high frequency. From simple physical reasoning we found that the solar radiation maintained an electric double layer with surplus of positive charge in lower regions and a surplus of negative charge in the form of an electron cloud, probably of large extension depending on the distribution of energy among the photoelectrons and the maximum effective frequency. At the lower part where the density is so small that the mean free-path does not exceed, say a few km, equation (25) may be applied, and we see that the existence of a positive volume-charge and an upwardly directed force will have the effect of reducing the influence of gravity and the rate at which the density diminishes upward. In other words, matter will be driven toward greater altitudes through the effect of the electric field. When finally the density becomes very small and the mean free-path very long, the positive ions may gain so much energy during their free motion between two collisions as to acquire the properties of upwardly moving positive rays. These rays will sooner or later—just as in the case of canal rays—pick up electrons and become neutralized or even negatively charged, and then fall down again.

An approximately stationary state will be reached depending on the intensity and composition of the solar rays of short wave-length reaching the locality considered. In the stationary state, Poisson's equation may be applied to the average values of σ and F or

$$(\partial F/\partial r) + (1/r \cos \varphi)(\partial F/\partial \lambda) + (1/r)(\partial F/\partial \varphi) = 4\pi\sigma \qquad (26a)$$

where φ and λ are latitude and longitude. Assuming the direction of F to be nearly vertical, we have, approximately,

$$(\partial F/\partial r) = 4\pi\sigma = (\partial F/\partial h) \qquad (26b)$$

The resulting electrical state of the atmosphere as a function of altitude will be something like that illustrated in Figure 19. Curve 1 gives the vertical electric force, curve 2 gives the electric volume-density, σ, and curve 3 gives the probable value of electric conductivity due to the presence of ions and electrons.

At a certain altitude, A, the electric force changes sign. The electric volume-density is positive from the ground to a level B, with one maximum near the ground and one at the lower part of the auroral region just above level A. Above B we enter into a highly ionized region with surplus of negative electrons. The positions of the various levels and the distribution of force and charge will be subject to large fluctuation. At a definite time the state, at a certain locality, will be mainly a function of the *angular* distance to the Sun. The amount of matter and electric charges driven toward higher altitudes will be a maximum at the spot which has the Sun in the zenith.

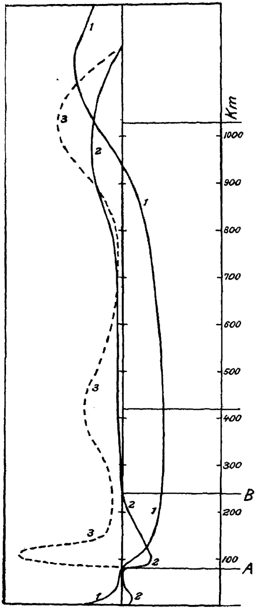


FIG. 19.—Electric state of atmosphere as a function of altitude (curve 1 = vertical electric force, curve 2 = electric volume-density, curve 3 = probable value of electric conductivity due to the presence of ions and electrons.

If in the auroral region we construct surfaces of equal density, they will have a maximum altitude near the place where the Sun is in zenith at the moment. The distribution of matter, being largely due to the motion of charged particles, will be influenced also by the magnetic field of the Earth. The electric rays moving toward higher altitudes will have a tendency to follow the magnetic lines of force and thus matter will tend to accumulate in the plane of the magnetic equator. This effect is well illustrated by an experiment of Birkeland shown in Figure 20.

In this experiment the sphere at the center of the vacuum-chamber is a cathode, and we see that the electrons accumulate in the plane of the magnetic equator.

As a result of the solar action, matter is driven out toward greater altitudes and, on the side of the Earth facing the Sun, the atmosphere extends into a system resembling the Sun's corona and which might be called the terrestrial corona [1372]. As soon as the radiation from the Sun ceases to act (on the nightside of the Earth), the electric field above the level *A* is quickly reduced to zero and matter begins to fall to establish the night conditions with a much more rapid fall of the density of matter than that existing on the dayside. In other words, the extension of the terrestrial corona is greatly reduced.

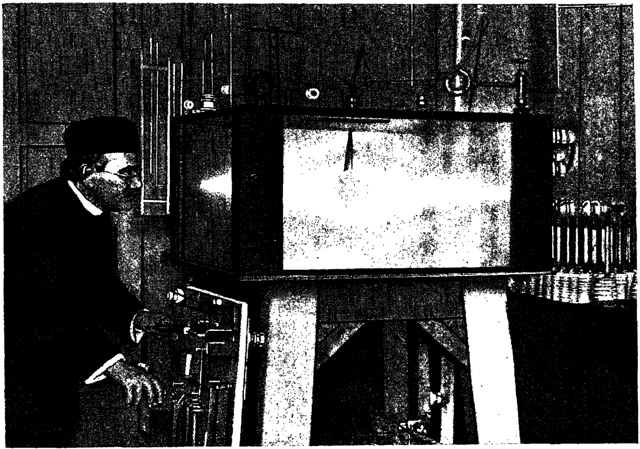


FIG. 20.—Experiment of Birkeland with cathode sphere at center of vacuum-chamber showing electrons accumulating in the plane of the magnetic equator.

As a consequence, Vegard found [847] that the maximum height of auroral rays, other conditions being the same, ought to increase toward lower latitudes and be larger near sunset than during the middle of the night. Both these consequences have been confirmed by the very important measurements of height by Störmer, already referred to. He found that the maximum altitude is larger near Oslo than near the auroral zone and that auroral rays reach exceptionally great altitudes just near sunset, when the Sun is still illuminating the auroral region. Later in the evening, when the solar rays have disappeared from the auroral region, the auroral rays become shorter. This most important result is illustrated in Figure 3 taken from one of Störmer's papers.

The ions moving in the electric field set up as the result of solar action may acquire a velocity sufficiently large to enable them to excite luminescence and to produce ionization. Because of the slow rate of recombination, the highly ionized state and the activated nitrogen may last throughout the night and, the recombination continually going on, may result in the excitation of luminescence partly through collisions of the second kind. Thus we may explain the luminescence shown by the night sky. If the green auroral line is formed by the action of active nitrogen, we understand that this line may appear strong in the spectrum of the night sky while the rest of the night-sky spectrum differs considerably from that of the aurorae, which primarily is due to the impact of the solar electric rays [1379].

This view has been strongly supported by results obtained with regard to the spectrum of the night-sky luminescence. During the years 1934–35 Vegard and Tönsberg [1383-*A*] carried out investigations in order to compare qualitatively and quantitatively the night-sky spectrum with that of the aurora. Among the results we may mention the following:

(*a*) The first positive group of nitrogen appears in the night-sky spectrum, but the number of bands is much smaller than in the case of the aurora and the bands show an intensity-distribution essentially similar to that of the afterglow from active nitrogen.

(*b*) In the case of typical night-sky luminescence, no trace of the second positive or the negative group of nitrogen is found in the spectrum. When these bands sometimes appear, they are probably due to the presence of auroral luminescence.

(*c*) The oxygen triplet, $OI(^1D_2 \rightarrow {}^3P_{012})$, appears in the spectrum of the night sky and its intensity varies considerably just as in the case of the aurora. This indicates that the intensity-changes are due to variations in the composition or state of the upper atmosphere.

(*d*) Compared with the green line the intensity of the bands of the first positive group is much greater in the night sky than in the auroral luminescence.

(*e*) The appearance of the forbidden oxygen lines, $OI(^1S_2 \rightarrow {}^1D_2)$ and $OI(^1D_2 \rightarrow {}^3P_{012})$, shows that the luminescence of the night sky originates from the auroral region where the pressure is extremely low. After the emission of the first positive group the nitrogen molecule is left in the metastable $(A\,^3\Sigma)$-state, which forms the upper level of the ϵ-system. As this system appears in the auroral spectrum, it should also appear in the night-sky luminescence. In fact, Cabannes and Dufay [1314-*A*] observed a considerable number of ϵ-bands in the night-sky luminescence. Recently, Bernard [1311-*A*] and Cabannes and collaborators [1314-*B*, 1314-*C*] proposed to identify a yellow line or band in the night-sky spectrum with the sodium *D*-lines. The presence of considerable quantities of sodium in the upper atmosphere seems rather improbable and the proposed interpretation meets with considerable difficulties; one must wait for further tests before expressing any definite opinion on the matter.

We have an important source of information regarding the state of the upper atmosphere from the study of the influence of these higher strata on electric waves. Results already obtained by a number of authorities in this field [942, 950, 992, 1436] point to an electric state of the upper atmosphere essentially the same as that found from auroral investigations. This is the more remarkable as the two lines of investigations deal with very different phenomena and effects. Through the aurorae we investigate the distribution of matter from the luminescence produced, and from this distribution we are led to the electrical state as a consequence; from the radio-echo work, however, we try to estimate directly the electric conductivity and electron-concentration at various altitudes (see Chapters IX and X).

Referring to Figure 19 (curve 3) we see that the theory of the upper atmosphere, which is based on auroral investigations, leads to the existence of at least three layers of maximum ion-density. An upper one results from the rapidly moving photoelectrons released through the action of the soft X rays from the Sun and, on account of the great mobility and large mean free-path of these electrons in the extreme upper stratum, this ion-maximum is not restricted to the dayside, but surrounds the whole Earth [compare reference 1380-*B*]. This maximum corresponds to the ordinary F_2-layer.

The X rays will produce a second maximum farther down in the atmosphere, where the absorption per unit-length of path is a maximum. *For various reasons, Vegard* [1380-*B*] *assumes this maximum to be the lowest of the three and to correspond to the so-called E-layer.*

The ionization-maximum in the middle is produced, according to Vegard [1380-*B*], by the rays of short wave-length in the interval between ultraviolet light and X rays. The absorption-coefficient within a broad interval, say between 100 and 800 Ångstroms, is very small and should give ionization-maxima at nearly the same altitude.

Reasonable assumptions regarding the absorption-coefficient and the distribution of matter in the atmosphere *would place this ionization-maximum at a height of about* 200 *km which would correspond to that of the* F_1*-layer.*

In accordance with observations, the theory leads to the consequence that the *E*- and F_1-layers are restricted to the dayside while the F_2-layer is ordinarily observed throughout the night.

This theory of the upper atmosphere, combined with the theory of the aurora and polar magnetic disturbances developed by Birkeland and Störmer, also explains the peculiar behavior of the ionospheric reflections during magnetic disturbances.

When the electric precipitations enter into the atmosphere an ionization-maximum is formed at a height which must be nearly equal to that at which we observe the lower limit of the aurorae. Thus a layer at a height of about 100 km is formed, or it has about the same height as the *E*-layer. Therefore, it is usually called *E*-layer, although it has quite a different physical origin. We therefore call it E'-layer.

As the rays carry negative electricity, they will disturb the stationary state of the F_2-layer. The electrostatic field which prevents the rapidly moving photoelectrons from leaving the Earth will be locally reversed; the F_2-layer will move upward and be more or less split up and disturbed.

The electric charge carried by the electrons will set up electric currents which will have the effect that the ions will spread out to the sides and also downward. The increased ion-density at lower altitudes will produce a great absorption and for somewhat strong perturbations the echoes disappear altogether. This phenomenon was discovered by Appleton and his collaborators and they assume that the disappearance of the echoes is due to absorptions taking place below the reflecting layer [952, 960]. This is in agreement with the consequences drawn from our theory of the auroral region.

The disappearance of the echoes during polar magnetic storms is in effect somewhat similar to the so-called "fade-out" phenomenon [977]. But while the disappearance of the reflections due to polar perturbations usually occur in the night, the "fade-outs" are typical day phenomena. They are accompanied by a peculiar type of magnetic perturbation, which has been described by McNish [416], and it follows from his studies that we are dealing with the type which Birkeland called cyclo-median storms.

From the theory here given regarding the constitution of the auroral region, the occurrence of the "fade-outs" merely indicates that occasionally the Sun emits X rays which have somewhat shorter wave-length than those which are constantly emitted and which produce the *E*- and F_2-layers. More details with regard to the theory of the auroral region and the explanation of the radio-echo phenomena will be found in a paper recently published [1380-*B*].

(4) ZODIACAL LIGHT, SOLAR CORONA, AND COMETS' TAILS

As already mentioned, the action of the Sun's rays of high frequency will result in the formation of a "terrestrial corona" directed toward the Sun; to a certain extent, it is influenced by the magnetic field of the Earth, and so it will take the form of a lens—the axis of which coincides with the magnetic axis of the Earth—with its largest extension on the dayside. *When after sunset the Sun still illuminates the terrestrial corona, it will appear as a cone of light and, as the corona has its largest extension toward the Sun, it appears as if the luminous cone were due to scattering of light by particles distributed near the plane of the ecliptic. Hence the name zodiacal light.* According to this view, the zodiacal light should be chiefly reflected sunlight but, in addition, the terrestrial corona should emit a luminescence typical for the matter forming it and essentially the same as that observed from the night sky. Spectral analysis of the zodiacal light by Slipher has given results in good agreement with this view.

Vegard [1369, 1372, 1374] indicates that the formation of the terrestrial corona can be directly applied to the conditions on the Sun and gives a very simple theory of the solar corona. The primary cause of the formation of the solar corona is found in the emission of high-velocity electrons from the surface of the Sun. It is immaterial whether these electrons are photoelectrons or electrons which have obtained their kinetic energy in some other way. When the electrons leave the Sun, electric fields are set up and positive ions will follow in their track. The length of the streamers is essentially a function of the kinetic energy of the electrons, while the density of the streamers is determined by the intensity of their emission.

The law of distribution of matter is determined by the distribution of the velocities of the electrons which are producing the coronal streamers. The variation of the corona with the sunspot-cycle gives us an idea of the variation with regard to distribution of intensity and velocity of the electrons emitted from the Sun. At sunspot-maximum the intensity of the emission of electrons should be a maximum and the average velocity a minimum; the result is a dense corona of small extension. At sunspot-minimum the intensity of the emission of electrons should be a minimum and the average velocity a maximum; the result is a thin corona with very long streamers. It was mentioned in a previous paragraph that the solar electric rays producing aurorae and magnetic storms probably have a constitution similar to the streamers forming the solar corona. Vegard [1379] indicated that the aurorae, with red bottom-edge *reaching the lowest altitudes*, seem to appear at the time of sunspot-minimum, when the large extension of the coronal streamers indicates that the electron rays *have their maximum velocity.* The mathematical treatment of Vegard's theory of the solar corona is essentially the same as that involved in the theory of the distribution of matter in the upper atmosphere on the dayside of the Earth (terrestrial corona). An attempt at such a mathematical theory was first made by Vegard [847], and the problems involved in the theory have been treated by Rosseland [1334].

Some years ago, Vegard [1369, 1372] showed that the electric fields resulting from photoelectric action of the Sun's rays may give a simple explanation of the development of the comets and their tails. As the result of photoelectric effect of solar rays of high frequency, a kind of coronal structure develops round the central body of the comet. The gravitational field produced by the comet being extremely small, a minute electric field will be sufficient to carry the positively charged matter away from the comet. As the distance from the center of the comet increases, the weak local field becomes insignificant as compared with the field of the Sun, which, for example, may result from the electric action of cosmic rays. In order that positive ions may be driven away from the Sun, the electric force, due to the Sun's field near the comet, needs be only of the order of magnitude of 10^{-10} ESU.

In the case of both the solar corona and the comets' tails, we shall have to consider the influence of light-pressure in the way proposed by Milne. According to the light-pressure theory, atoms and molecules are the primary corpuscles driven out and electrons are merely made to follow in so far as the atoms or molecules are positively charged. Such bundles would not account, as we saw, for the auroral phenomena. Further, we should expect, as pointed out by Chapman, to find effects in the higher atmospheric strata due to the precipitations of neutral particles not influenced by the magnetic lines of force and, therefore, falling on the dayside of the Earth. On the other hand, the electric rays producing aurorae and magnetic disturbances are found to have a penetrating power larger than that which can be obtained by light-pressure and to be mainly composed of electrons. Therefore, we have to assume that electron rays of high speed are emitted from the Sun from other causes than light-pressure. The development of the terrestrial corona from the solar rays of high frequency makes it necessary to assume also that matter is driven away from the Sun as the result of the action of the same radiation acting on the solar atmospheric matter. No doubt, therefore, the photoelectric action of the Sun's rays and the emission of high-speed electrons play a prominent part in the development of the solar corona; but this does not exclude the idea that the light-pressure also may have a large influence. The same may apply to the formation of comets' tails.

CHAPTER XII

THUNDER-CLOUDS, SHOWER-CLOUDS, AND THEIR ELECTRICAL EFFECTS

B. F. J. Schonland

The Bernard Price Institute of Geophysics, University of the Witwatersrand

The thunder-cloud is studied in atmospheric electricity as the limiting case of a disturbed electric field in the air, the limit having been reached by the occurrence of electrical breakdown and the passage of a spark-discharge. Since many of its effects are found to be associated with shower-clouds, in which the critical field is not reached, they are conveniently studied together.

That a thunder-cloud is an electrostatic generator was shown in 1752 by the celebrated experiments of Franklin, Dalibard, and de Romas, and some further characteristics of this generator can be simply stated. The seat of the generation of electricity being within the cloud itself, the machine separates out equal quantities of electricity of opposite sign from one another and places them—though now not necessarily equal, for their rates of dissipation may differ [524, 786]—in different parts of the cloud. As the process of separation proceeds, the electric field between these "poles," or sometimes between one of them and the Earth, grows until breakdown occurs. A conducting channel is then produced which leads rapidly to the disappearance of part at least of the charges originally separated.

To obtain further details as to the cloud-machine it is necessary to make quantitative observations of the electric fields of thunder-clouds and rain-clouds and of their time-variations, of the charges and currents carried in lightning-discharges, and of the charges carried by rain-drops.

I. ELECTRIC FIELDS AND FIELD-CHANGES AT THE EARTH'S SURFACE

The electric field produced at the ground by a thunder-cloud is constantly altering, reaching maximal values just before lightning-discharges and minimal values just afterward. These changes and those due to the recovery of the cloud-charges are superposed upon others which arise from the movement of the cloud as a whole and from internal movements in the cloud. If the thunder-cloud is distant, the less strongly charged but nearer rain-clouds may interfere with the observations. The variation of thunder-cloud fields in both time and magnitude is such as to make it necessary to employ special methods in their study. This was first done by C. T. R. Wilson [786], who used the method of the exposed conductor, maintained at earth-potential by an automatically compensating capillary electrometer. The instrument yields records of the type shown in Figure 1, in which *A* and *B* are negative and positive field-changes, respectively. It is frequently found that the field recovers after a discharge in a manner which approximates closely to the exponential form. This initial recovery rate is referred to by Wilson in terms of the time, $\Delta F/(dF/dt)$, which would have sufficed for full recovery if the initial rate had continued unaltered. The Wilson apparatus yields values for the actual field at any time by employing a device which screens the exposed conductor from the field at regular intervals. The cathode-ray oscillograph has been utilized by Norinder [751, 752] and by Appleton and Chapman [954] in the study of field-changes due to near discharges and by Appleton, Watt, and Herd [966] for more distant ones. The radioactive collector and quadrant-electrometer have been employed by some observers for obtaining general information on the electric field, and field-changes have been studied qualitatively by using exposed conductors connected to earth through ballistic galvanometers. A method of recording the field and its changes which utilizes the current discharged from a sharp point has been developed by Whipple and Scrase [621]. A novel method of studying the field within, as well as below and above, a thunder-cloud has recently been developed at Kew Observatory. This makes use of point-discharge and pole-finding paper in an instrument attached to a sounding balloon [778].

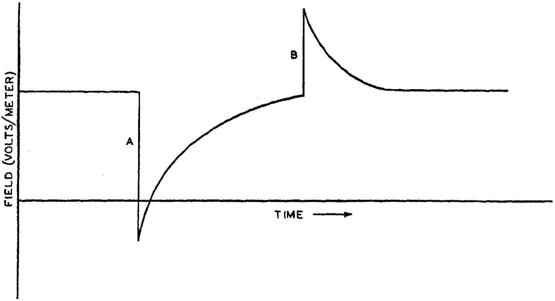


FIG. 1.—Electric field of a thunder-cloud and its changes with lightning-discharges (*after C. T. R. Wilson*).

(1) SIGN AND VALUE OF THE ELECTRIC FIELD [786]

It is convenient, in view of the time-variations referred to above, to use the term pre-discharge field for the field at the moment when the thunder-cloud is on the point of discharging. When the cloud is about 20 km off, this has a value of the same order as the fine-weather field—about 100 volts per meter and is negative in sign (that is, the Earth appears positively charged against the air). As the cloud approaches the observing station, the field rises rapidly and often attains a pre-discharge value of 5,000 volts per meter at a distance of six km. When the cloud is within a few km, the pre-discharge field ranges from 10,000 to 30,000 volts per meter and does not usually rise higher than this. The sign of these high pre-discharge fields is most generally negative, although observations of positive field are not infrequent. Schonland reports [763] that in the case of storms from which little rain is falling, this negative field usually persists while the whole base of the cloud passes overhead. When heavy rain is falling, the field may reverse to a strong positive value for some time, though it is still generally negative when the active center is closest to the observer. In cases of positive field, it is observed that the pre-discharge field is generally less positive than the field at other times, suggesting that the same mechanism which produces high negative pre-discharge fields in dry storms is operating, but that its effects are superposed on a positive field arising from some other cause. Cases of reversal of the field from negative to positive values as the center of the storm passes overhead have been found by Banerji to be common in India [729].

As in the case of thunder-storms, the strong electric fields below shower-clouds are most generally negative in sign and often attain values as high as 10,000 volts per meter.

Several observers have reported cases where the negative pre-discharge field from overhead storms was associated with a reversal to small positive values when the same clouds were about 10 km distant [761, 771, 791].

(2) DISCHARGE FIELD-CHANGES

All observers agree that when the active center of a thunder-cloud is near, the field-changes due to lightning are predominantly positive in sign. In storms where lightning-discharges to ground are infrequent it is found that a reversal in the sign of the majority of the field-changes occurs when the cloud is more than 10 or 15 km away from the observer. This reversal effect, first observed by Appleton, Watt, and Herd [966], has been studied in South Africa by Schonland and Craib [763, 771] and by Halliday [739]. Some data on it are shown in Table 1.

TABLE 1.—*Sign of discharge field-changes*

Distant storms			Near storms		
Distance, km	Positive changes	Negative changes	Distance, km	Positive changes	Negative changes
>15	250	2,375 (Schonland)	<5	54	16 (Wilson [786])
>10	113	644 (Halliday)	<7	563	70 (Schonland)
			<6	86	18 (Halliday)
Totals	363	3,019	Totals	703	104

It has been established that this reversal of sign is associated only with discharges which take place within the cloud. It has been shown, by correlating field-changes with observation of the flashes, that a very high proportion ($\frac{654}{669}$) of distant intercloud-discharges give rise to negative field-changes [739, 763]. The sign of these changes reverses at a distance of from 15 to 5 km from the observer, depending on the height of the cloud.

In the case of flashes to ground it has been shown that the field-change is generally positive at all distances, as exhibited by Table 2.

TABLE 2.—*Field-changes due to flashes to ground at all distances*

Positive changes	Negative changes	Observer
67	4	Schonland
267	16	Halliday
77	13	Jensen [743]
411	33	

The magnitude of the field-changes is in general of the same order as the pre-discharge field, with maxima of some 20,000 volts per meter when overhead. Occasional higher values are reported—150 kv/meter (Norinder [752]), 270 kv/meter (Matthias [749]), 165 kv/meter (Peek [756]).

(3) POLARITY OF LIGHTNING-STROKES TO ELEVATED CONDUCTORS [784]

Table 2 indicates that the majority of lightning-strokes to ground convey a negative charge. This is in accord with observations on the polarity of direct strokes to elevated conductors [736, 748, 784]. Thus Lewis and Foust [748] find that practically all such strokes examined by them came from negatively charged portions of the thunder-cloud—certainly more than 87 per cent ($\frac{241}{277}$).

(4) FINE-STRUCTURE OF FIELD-CHANGES

The field-change observations referred to above are concerned with net changes, which may last as long as one sec. The photographic evidence as to the nature of lightning, discussed in Section XIII, indicates that these changes must have a complex structure. The structure was first studied for near discharges by Norinder [751], using a fast cathode-ray oscillograph, who found aperiodic changes with superimposed ripples. It has recently been more completely examined by Appleton and Chapman [954], who report that each field-change component which corresponds to a stroke or partial discharge of the flash consists of three parts, namely, a comparatively slow change, a rapid and larger change, and a final slower and smaller change. These authors advance reasons for identifying the first two portions with the leader stage and rapid-return stage of the lightning-stroke discovered photographically by Schonland and Collens, who have supported and extended this identification in a later paper [770].

II. THE CHARGE ON RAIN

An exhaustive examination of the charge carried by rain from thunder- and shower-clouds was made from 1907 to 1909 in Simla by Simpson [724]. His observations showed a preponderance of positive charge on the rain, the total quantity observed of this sign being three times as great as the quantity of negative charge. The strongest charges are found to be carried by the less violent rain from the rear of the storm. The preponderance of positively charged rain, however, increases with the heaviness of the rainfall. This preponderance is not observed in all storms [729].

III. THE BREAKDOWN FIELD IN THE PRESENCE OF DROPS

In air at normal pressure and temperature the value of the critical field at which spark-breakdown occurs is 30,000 volts per cm. In a thunder-cloud the pressure is lower and the presence of water-drops introduces a new factor. Macky [717] has shown that drops of radius r cm, when placed in strong electric fields, become elongated and unstable at a field-strength given in volts per cm by $F\sqrt{r} = 3{,}875$. The critical value of F is independent of the air-pressure over a wide range. Macky concludes that no drops of radius greater than 0.15 cm can be present in the fully charged cloud and that the breakdown value of the field in the presence of water-drops is of the order of 10,000 volts per cm.

IV. THE CHARGES DEVELOPED AND OTHER ELECTRICAL QUANTITIES INVOLVED IN THE THUNDER-CLOUD

The study of discharge field-changes enabled Wilson [786] to devise a remarkable and unambiguous method of determining the *quantity of electricity* removed by a lightning-flash and hence led to the deduction of a number of other quantities concerned in the electrification of a thunderstorm. Consider a charge, Q, distributed through a spherical region with its center at a height, H_2, above the ground. The electric field at a point on the Earth at a horizontal distance, L, is then given by

$$F = 2QH_2/(H_2^2 + L^2)^{\frac{3}{2}}$$

vertically downward. If a lightning-discharge causes Q to pass to a lower level, H_1, the discharge field-change is evidently

$$\Delta F = 2Q[H_1/(H_1^2 + L^2)^{\frac{3}{2}} - H_2/(H_2^2 + L^2)^{\frac{3}{2}}] \tag{1}$$

In the important case where the distance, L, is great compared with H_1 and H_2, equation (1) takes the form

$$2Q(H_1 - H_2) = \Delta F \times L^3 \tag{2}$$

which is not dependent on the assumption of a spherical distribution of charge if L is also large compared with the dimensions of the charged region. The quantity on the left in equation (2) is the difference between the electric moments of the charge, Q (combined with its mirror-image, $-Q$, in the conducting Earth) before and after the discharge. It is termed by Wilson the electric moment of the discharge.

Equation (2) is equally applicable to the case of a discharge to ground, when H_1 is zero, to that of a discharge in which a charge, Q, merely passes upward or downward within the cloud, and to that of a discharge in which Q at a height, H_2, neutralizes an equal and opposite charge, $-Q$ at H_1. In the last case the effect of adding the field due to $-Q$ to both F_2 and F_1 disappears in computing ΔF by equations (1) and (2).

The average value of the discharge-moment found by Wilson in England is 2×10^{16} ESU or 60 coulomb-km. The average vertical length of a discharge was taken by him as 1.5 km. Thus he found 20 coulombs for the average quantity discharged by a flash of lightning. The corresponding quantities determined by Schonland [764] in South Africa, using the same method, were 90 coulomb-km, 2.2 km, and finally again about 20 coulombs. The range of variation in Q is from 2 to 100 coulombs if the value of $(H_2 - H_1)$ be supposed constant and would probably be much less if the flash-length could be observed in every case.

Appleton, Watt, and Herd [966], using both the very small net change electrostatic field and the radiation-field produced by very distant discharges, have deduced somewhat larger values for the discharge-moment, 2×10^{17} ESU.

(1) INITIAL RECOVERY-CURRENT

The initial recovery-time, which would have sufficed for full recovery of the charges if the rate had continued, has been found by Wilson [786] to vary from 1.5 to 30 sec with a mean value of 6.9 sec. In more than half the cases examined it lay between four and ten sec. Schonland

[764], in the case of tropical storms, finds values ranging from two to ten seconds with a mean about four seconds.

If we take five seconds for this quantity, it follows that the cloud initially produces a current of $\frac{20}{5}$ or four amp immediately after a discharge. The question whether this rate actually continues and the growth of the charges is exponential because hampered by dissipation-effects or whether the rate itself decreases as the charges grow is not yet decided.

(2) DIMENSIONS OF THE CHARGED REGIONS AND POTENTIAL REACHED

To determine these quantities Wilson [786] made use of the following simple argument: Consider first a spherical distribution of a charge, Q, inside a sphere of radius, R. When breakdown is first reached at the surface of the field, F, there is $F = Q/R = 33$ ESU, while Q is 20 coulombs. Hence, R is found to be 427 meters and the dimensions of the charged region are of the order of one km.

The potential at the surface of such a sphere is then

$$Q/R^2 = FR = 4.3 \times 10^8$$

volts, while if the radial electric force within the sphere is everywhere at the critical breakdown value the potential at the center would be $2FR$ or 9×10^8 volts. It follows that two such spheres carrying opposite charges would be at a difference of potential of the order of 10^9 volts.

The value thus obtained for the potential difference between the cloud-poles is of the same order as that which follows from consideration of a stratiform cloud with its two poles distributed in horizontal layers and separated by a vertical thickness, L, of neutral water-drops [786]. This thickness is known to lie between one and six km. At the breakdown point the critical value of the field is 10,000 volts/cm and thus the difference of potential between the poles must lie betweein 10^9 and 6×10^9 volts. This last value probably represents the upper limit to the potential difference attained by a thunder-cloud.

(3) MEAN DENSITY OF CHARGE [786]

From the data given above a cloud-pole may be estimated to carry 20 coulombs in a spherical region of radius 500 meters, giving a charge-density of 120 ESU per cubic meter. Consideration of the stratiform cloud at the point of discharging gives 80 ESU/cubic meter for the same quantity. If we take 100 ESU/cubic meter as the mean, and the amount of water to be the same as that in ordinary rain-clouds, 4 gram/cubic meter, the charge per gram of water is found to be 25 ESU. This value is of the same order as that found for heavy rain. Drops carrying charges of this nature and in a field approaching the breakdown value would be subjected to forces of electrostatic origin which are comparable with their weight and which must play a part in holding up charged rain within the cloud.

(4) ENERGY AND CURRENT IN THE LIGHTNING-DISCHARGE

The fall of 20 coulombs through a potential difference of 10^9 volts involves the disappearance of electrical energy amounting to 10^{17} ergs or 2.5×10^9 calories [786]. Most of this is converted into light, heat, and sound along the channel of the discharge.

The total duration of the discharge is dependent on the number of separate strokes (Section XIII) and may attain about one sec. A powerful single stroke has an effective duration which does not exceed 200 microseconds and its most intense character lasts for a still shorter time [770]. An estimate of the current in the discharge thus gives $\frac{20}{2} \times 10^{-4}$, or 100,000 amp, over a period of 200 microseconds.

(5) ENERGY SPENT IN PRODUCING LIGHTNING

A cloud giving one flash every 20 sec would be dissipating energy in the form of lightning at the equivalent of a continuous expenditure of 10^6 kw [786]. Other factors may require further development of power of the same order of magnitude. It will be seen (Section VI) that the action of gravity on the water in the cloud is capable of supplying the necessary mechanical energy for this development of electrical power.

V. THE DISTRIBUTION OF CHARGE ON THE THUNDER-CLOUD

Various workers have utilized the observational data described above to deduce the manner in which the charges are distributed in thunder-clouds, though general agreement has not yet been reached.

C. T. R. Wilson [786] has suggested a distribution in which the positive charge is elevated above the negative and separated from it by a region so filled with both positively and negatively charged rain-drops as to be effectively neutral. Such a cloud is termed by him a cloud of positive polarity. Evidence supporting such a cloud-model has been given by a number of obervers and may be summarized as follows: *Field-changes* produced by intercloud-discharges in such a model would be positive when near and negative when distant, as shown at once by equation (1). They would reverse in sign at a distance, L_0, given by

$$H_1/(H_1^2 + L_0^2)^{\frac{3}{2}} = H_2/(H_2^2 + L_0^2)^{\frac{3}{2}}$$

On the other hand, a discharge to ground from the negatively charged base of such a cloud would produce positive field-changes at all distances, as shown in Table 2. The *pre-discharge field* from a cloud of positive polarity is given by a simple extension of equation (1) to the case where the field due to charges Q_2 and $-Q_1$ at heights H_2 and H_1 is required [791].

It is found to be $F = 2Q_2H_2/(H_2^2 + L^2)^{\frac{3}{2}} - 2Q_1H_1/(H_1^2 + L^2)^{\frac{3}{2}}$. For near storms, when L is small, the second term, representing the effect of the lower negative charge, should be the greater (unless $Q_2 > Q_1H_2^2/H_1^2$). This result thus accounts for the prevalence of negative fields below the cloud, though not for the effects observed by Banerji [729]. For distant storms, the first term, which represents the effect of the upper positive charge, will predominate (unless $Q_2 < Q_1H_1/H_2$). Thus in general it would be expected that the pre-discharge field would exhibit a reversal, though at a different distance from that for reversal of the field-changes [763, 771, 791].

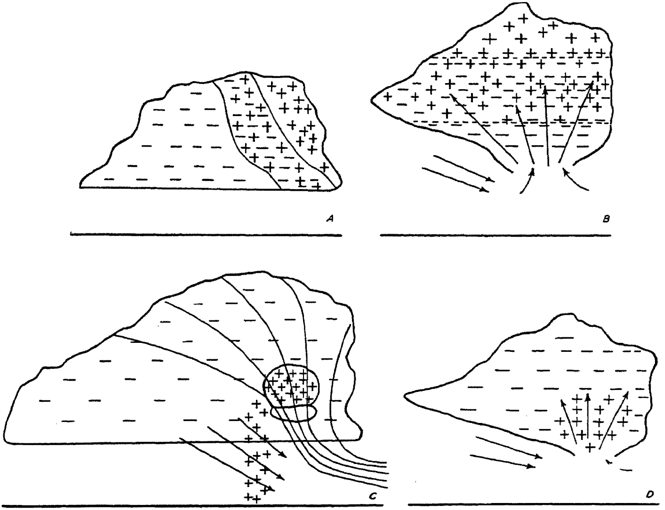


FIG. 2.—Distribution of thunder-cloud charge suggested by H. Norinder (*A*), C. T. R. Wilson (*B*), G. C. Simpson (*C*), and S. K. Banerji (*D*).

A distribution somewhat resembling that of Wilson has been suggested independently by Norinder [752] as a result of observations on fields and field-changes, and is shown in Figure 2-*A*. The ideal case for a cloud of positive polarity is shown in Figure 2-*B*, though no actual application to meteorological conditions has yet been made by the supporters of this view.

Distributions suggested by Simpson [776] and by Banerji [729] are shown by *C* and *D* of Figure 2. They have in common the feature that the positive charge is confined to a region fairly low down in the cloud and surrounded by negative charge. A discussion of some of the field-change observations in terms of this model has been given by Simpson [776] and replied to by Schonland [763] and Halliday [739]. The chief difficulty in fitting such a distribution to the field-changes observed is the practical absence of any observations of intercloud-discharges involving the upward movement of positive charge, which would give rise to positive field-changes at a distance. As mentioned in Section I-2, Schonland and Halliday found that such field-changes were associated with only two per cent ($\frac{15}{659}$) of intercloud-discharges.

Nukiyama and Noto [666, 753] have reported observations which support the Wilson distributions and others in which it would seem that the inland, as contrasted with the coastal, storms of Japan have the Simpson type.

It is unfortunate that no other satisfactory means of distinguishing between the proposed charge-distributions than that based on fields and field-changes have yet been developed.* Two proposed criteria, the branching of lightning-discharges and the charge on rain, have been shown to be ambiguous.

(1) THE LIGHTNING-BRANCHING CRITERION

The electric spark in the laboratory shows branches directed away from the positive pole, and this fact has often been used as a means of determining the polarity of the two ends of a lightning-discharge. An examination of a large number of lightning-photographs led Simpson [775] to the conclusion that upwardly directed branches were exceedingly rare and consequently that the polarity of that part of the cloud-base which produced flashes to ground was negative. This deduction is contradicted by the field-change evidence (Table 2) and by observations (Jensen [743], Halliday [739]) which involved simultaneous photography of the appearance of the lightning and the net field-change produced.

It was shown by Schonland and Allibone [769] that branching away from the negative pole can be realized in the laboratory provided the conditions prevailing below a thunder-cloud were more closely imitated. The branching criterion has, therefore, disappeared as a means of determining polarity, though Jensen [743] has published evidence which suggests that a discharge from a seat of positive charge results in more finely branched streamers than one from a negative cloud-charge.

VI. THE ORIGIN OF THE CLOUD-CHARGES

Four theories have been advanced in modern times to account for thunder-cloud and rain-cloud electrification, one of which has not survived criticism. Any such theory has to be able to show how the electricities of opposite sign can be separated and carried to different parts of the cloud in spite of their attractive forces. The mechanical power for such a separation is obviously available in the upward movement of the air which is characteristic of these clouds. But a further hypothesis must be made in order to show how the moving air can carry upward electricity of one sign and not of the other. All theories rest this further step upon a characteristic difference in size between the large rain-drops (diameter of order one mm) which constitute the dark base of the cloud and the small cloud-particles or droplets (diameter about 0.02 mm). The former have a terminal velocity of fall under gravity of some six meters per sec, in comparison with which the latter are practically stationary. Since the large drops can move downward in all but the strongest air-currents while the droplets are carried with the air, the theories are directed toward showing how the drops and the droplets can collect charges of opposite sign. In some accounts it is not clear whether a distinction is made between ordinary large ions and the droplets referred to, but in either case the theories apply. The conception of two main classes of cloud-particles (drops and droplets) is perhaps only a convenient simplification of what would otherwise be a complicated problem.

---

*But see footnote to section VI-1.

The *theory of Gerdien* [604, 629] attributes the selective action to the fact that supersaturated uprising air condenses on negative earlier than it does on positive ions, an effect first observed in the laboratory by Wilson. This would tend to produce a cloud-base of negatively charged drops, the air conveying the uncaptured positive ions with the droplets to the upper parts of the cloud. This theory has been abandoned, chiefly for the reason that the selective condensation required can be operative only in air free from Aitken nuclei and from droplets such as have been mentioned [589, 706, 774, 785].

The *theory of Elster and Geitel* [710] introduces a mechanism of the influence-machine type. It requires an initial polarizing field acting upon the drops so as to give them equal and opposite charges on their upper and lower surfaces. These polarization-charges [of amount $(\frac{3}{4})\,Fa^2$, where F is the field and a is the radius] are negligible in the case of the droplets. Relative to the latter, the polarized drops will be falling and frequent collisions will occur between drops and droplets at the under-surfaces of the former. A certain number of the droplets were considered to rebound from such collisions, carrying away the polarization-charge on the lower surface and leaving the drop with a net charge. The separation of drops and droplets in the air-stream thus enhances the original field and the process builds up as the polarization-charges increase. The starting field would in general be provided by the fine-weather gradient and the resulting cloud-charges would be positive above and negative below.

The theory in this form has been abandoned on account of the criticism [713, 726] that coalescence rather than rebound must take place in such collisions. Rebound can occur only if there is a film of air, which would prevent the passage of charge, between drop and droplet. The Elster-Geitel process is, however, probably effective in the case where the collisions are between hailstones.

The *theory of Simpson* [724, 776] is based upon an extension of the Lenard [716] effect, in which the breaking of drops of water produces droplets which recombine to form positively charged drops, while the air is given a charge of negative ions. Simpson showed that such a process can occur in the case of drops falling through an air-stream. The type of distribution to be expected from this mechanism is shown in Figure 2-*C*, in which the continuous lines represent stream-lines of the air and their distance apart is made inversely proportional to the wind-velocity at that point. The vertical velocity of the wind is taken to exceed eight meters per sec within the small oval region and through this region no drops can fall, since the terminal velocity of the largest stable drop (2.5-mm radius) is eight meters/second. In the roughly spherical region above, the positively charged drops will accumulate and be broken up, while the air will carry negative charge to the rest of the cloud.

Simpson has shown [776] that the mechanism is capable of developing charge at the rate required by thunder-storm observations, for if half the drops in the average cloud broke at the same time, some three to four coulombs of charge would be separated.

The breaking-drop process has also been studied by Lenard [716], Nolan [720], Nukiyama and Noto [722], and Zeleny [727]. The last has found a dependence of the charge developed upon temperature, air-velocity, and size of drop.

The *theory of Wilson* [789] represents an important advance on that of Elster and Geitel, whose polarized drops are now considered to be able to get a net charge by a process involving preferential capture of ions of one sign from the air-stream. In a vertical field of positive sign the lower surface of a drop is positively polarized, positive ions are moving down in the same direction as the drop, and negative ions are moving up. Suppose now that the velocity of the ions in the field is less than that of the drop, so that descending ions cannot overtake the drop. Those positive ions which are overtaken by the drop will be repelled by the lower polarization-charge before being attracted by the upper one and, since these charges are initially equal, it is to be expected that at first such ions will not strike the drop at all. The upward-moving negative ions which the drop meets will, however, be attracted by the lower polarization-charge and so give the drop a net negative charge. In this way the drops in the lower part of the cloud become negatively charged, the ascending air carries positive ions and positively charged droplets upward, the original field is enhanced, and the process goes on till breakdown occurs.

The condition that the ions shall have a smaller velocity than the drops can be met in two stages: For fields less than 400 volts/cm all types of ion, small as well as large, will be moving at less than six meters/sec, but for fields greater than this only the large ions and droplets can be effective in the process. Wilson has shown that the acquisition of a net charge by the drops does not seriously affect the possibility of further captures, for the enhancement of the field by the influence-process increases the polarization-charges.

If the field starting the influence-mechanism were that of fine weather, the thunder-clouds formed would be of positive polarity. This theory has been shown by Gott [713] to be in accord with experiments on artificially produced clouds.

(1) Discussion of thunder-cloud theories

At the present time it is not possible to decide whether the Simpson or the Wilson-Elster-Geitel process is more effective in producing thunder-cloud electrification. Most probably both processes are at work. The evidence concerning fields and field-changes appears, however, to require the positive charge to be elevated above the negative (Section V). This may give rise to difficulties in the operation of the Simpson mechanism, which could not work in the hail and snow region of the cloud.*

(2) The charge on rain

Simpson, who was the first to show that thunder-cloud rain is largely positively charged, has used this fact to support the distribution of charge and the theory as to its origin suggested by him [724, 776]. The falling out of positive rain from the densest part of the cloud is indicated in Figure 2-*C*.

The criterion has, however, been disputed by Wilson [524, 786, 789], who has given reasons why the sign of the charge on rain, as measured at the ground, may be the reverse of that which it had on leaving the cloud. He suggests that the preponderance of positive rain is linked with the preponderance of negative fields below thunder-clouds. In the first place, such fields will cause the lower air to be filled with positive ions due to point-discharge from the ground, and neutralization, followed by reversal, of the charge on a drop is to be anticipated. Secondly, a selective capture process by polarized drops will operate as they fall, the drops first becoming neutralized and then acquiring a net positive charge in the prevailing negative field. The process here occurs in fields of strength less than 400 volts/cm and can operate on small as well as large ions. It has been tested experimentally by Gott [713] in the case of water-drops falling through air containing small ions produced by X rays, with results in accordance with the theory.

---

* Experiments recently reported by G. C. Simpson and F. J. Scrase [778], using a potential-gradient recorder attached to a sounding balloon, are in accord with the conclusions of this paragraph. These show that the main distribution of charge is one with positive electricity in the upper, negative electricity in the lower layers of the cloud, the region of separation being below the freezing point. In addition they report the frequent but not invariable occurrence of a small region of localized positive charge in the negative base, which may be due to the breaking-drop mechanism.

VII. THE MECHANICAL POWER AVAILABLE FOR THE GENERATION OF CHARGE

The quantity of water in the average storm-cloud in the form of large water-drops has been estimated by Simpson to be 3×10^{11} grams [776]. This amount of water could produce mechanical energy equivalent to that dissipated by the storm in lightning-flashes (10^6 kw) by falling at the rate of only 30 cm/sec, whereas the terminal velocity of such drops is of the order of six meters/sec. There is thus plenty of mechanical power available in the gravitational mechanism on which all theories of thunder-cloud electrification must depend for the separation of charge. Quantitative examination of the mechanism can, however, be made only when the conversion of gravitational into electrical energy is taking place without appreciable losses by dissipation-currents to and from the cloud-poles. If we exclude dissipation by the falling out of charged rain, such conditions prevail immediately after the passage of a discharge between the cloud-poles. Following such a discharge, the charged drops and droplets in the neutral part of the cloud between the poles must on all theories* separate out with a relative velocity of some six meters/sec. Wilson [789] has shown, in the case of stratiform cloud, that if this fact be combined with the measured initial rate of regeneration of the discharge-moment, $\frac{60}{5}$ coulomb-km per sec, it follows that the average total charge of one sign on either set of carriers in the neutral part of the cloud is about 500 coulombs, occupying a volume of some four km^3. He has also pointed out that if gravitational separation is to continue to supply energy after the field has approached the breakdown value, and so to counteract dissipation-processes, the charge on the drops must not exceed 30 ESU/gm, as otherwise they would cease to fall.

VIII. INTERCHANGE OF ELECTRICITY BETWEEN ELECTRIFIED CLOUDS AND THE EARTH

An interchange of electricity between thunder- and shower-clouds and the ground can take place in three different ways.

---

* In Simpson's cloud-model the neutral region must lie in or just above the region of breaking drops.

(1) BY IONIC CONDUCTION

In the strong fields below such clouds, conduction-currents may assume very considerable proportions. Radioactive matter present in falling rain [782] and point-discharge from elevated conductors on the Earth provide additional ions for the transport of current.

The point-discharge effect, whose importance was first pointed out by C. T. R. Wilson [524, 787], has been studied by Wormell [790, 791] and by Schonland [764] and Whipple and Scrase [621]. Wormell has shown from long-continued observations that in temperate regions it is the most important factor in the interchange, while Schonland has shown that currents of the order of a few amp flow between the ground and the base of an active storm. Such currents must have an important dissipatory action on the cloud-charges and retard their general development.

Wormell's experiments indicate that point-discharge currents integrated over long periods are responsible in temperate regions for a net transfer of positive charge from the Earth to thunder- and shower-clouds. This conclusion is supported by observations of Whipple and Scrase [621].

(2) BY LIGHTNING [523]

A lightning-discharge to ground conveys an average charge of 20 coulombs (Section IV). In the majority of the cases so far examined this charge is negative (Table 2 and Section I-3).

(3) BY RAIN

This factor involves the transport of more positive than negative charge to the Earth (Section II).

The investigations on the total effect of these three processes which have so far been made support the suggestion of Wilson [524, 589, 706, 786, 787] that in regions of disturbed electric field the Earth gains sufficient negative charge to account for the losses it suffers by conduction in regions of fine weather.

IX. INTERACTION OF CHARGED CLOUDS WITH THE IONOSPHERE

The conductivity of the air increases rapidly with height, and the upper layers of charged clouds may be expected to be subject to considerable dissipation-currents passing between them and the *E*-layer of the ionosphere. Judging from what happens below the clouds, such currents should be mainly upwardly directed and result in positive charging of the ionosphere. Even without such evidence, the region in question, as Wilson has shown [524, 786], should possess a high degree of rectification in favor of upward currents since the negative carriers of the conduction-current at low pressures are electrons of much higher mobility than the positive ions. The conductivity of the ionosphere is sufficient to allow of the rapid distribution of the charge thus gained.

Wilson [787] has also pointed out that additional ionization in the *E*-region may be expected from the fact that the vertical field above a charged cloud diminishes slowly enough with height for cumulative ionization to occur at the low pressures prevailing in the upper air. The question has been further discussed by Appleton and Naismith [957], and evidence for the effect has been put forward by various observers [957, 1084, 1114].

X. ELECTROMAGNETIC RADIATION-ATMOSPHERICS [994, 1049]

Lightning-discharges are the chief source of the larger sudden field-changes detected by radio receivers, though not necessarily the only one. There is some evidence that static or atmospherics can be produced by charged shower-clouds from which thunder is absent. Long-distance direction-finding of atmospherics has been employed to locate the position and movements of centers of disturbed weather at sea and in uninhabited regions [746, 1068, 1112].

The nature of the radiation-field from distant discharges has been examined by Appleton, Watt, and Herd [966] with the cathode-ray oscillograph. They find the field-changes to be either aperiodic or quasi-periodic. The former type is nearly three times as frequent as the latter. The duration of the disturbed field has a mean value of two to three milliseconds, though values up to 20 milliseconds have been observed. Superimposed on the more slowly altering radiation-field they observed ripples of mean period 100 microseconds which in the longest case endured for three milliseconds. The ripples observed by Norinder [751; see Section I-4] from near storms have shorter periods, of the order of ten microseconds. It has more recently been shown [954] that the wave-form of an atmospheric alters with distance in a manner suggesting the action of a dispersive medium or of multiple ionospheric reflections [T. H. Laby and others, "Nature," **142,** 353, and **139,** 837].

XI. EMISSION OF ELECTRIFIED PARTICLES—EFFECT ON PENETRATING RADIATION

Schonland and Viljoen [773] have reported Geiger-Müller counter-observations which indicate that thunder-clouds are the source of electrified particles of high energy, which are emitted upward and subsequently brought down to Earth, at distances of about 100 km, by the action of the Earth's magnetic field. Similar effects have been observed by Cairns [773] (with an ionization-vessel), Appleton and Bowen [773] (at much greater distances), and Halliday (using a cloud-chamber) [741]. The

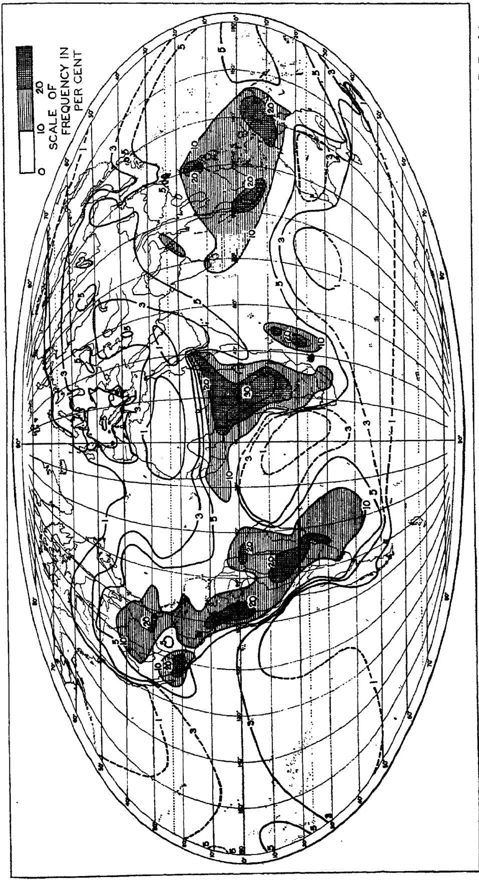


FIG. 3.—Annual distribution of thunder-storms over the globe, expressed in percentage of days on which thunder was heard (*after C. E. P. Brooks*).

last-named has found evidence that the emission takes place mainly from westerly storms, indicating that the particles are electrons.

That runaway electrons could be produced by thunder-clouds was first suggested by Wilson [788] who showed that a beta particle of radioactive origin emitted upward in the strong field within the cloud would rapidly increase in energy, gaining more energy from the field than it lost in ionizing collisions.

A reduction in the intensity of the penetrating radiation when charged clouds pass directly overhead has been reported by Schonland [765] and by Rizzo, who on August 27, 1932, made observations on Rocciamelone Mount, 3,537 meters above sea-level, as indicated in a brief note on page 584 of "Nature" for October 15, 1932.

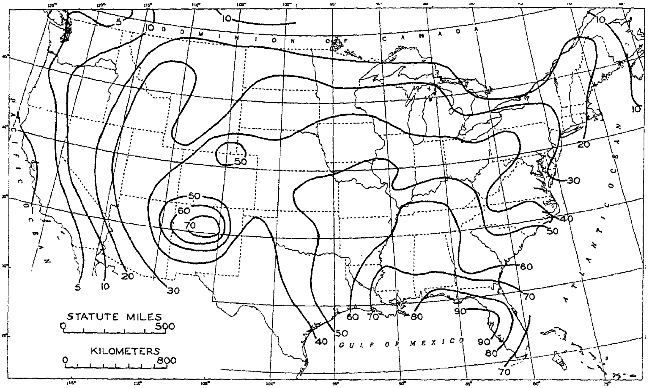


FIG. 4.—Isoceraunics or number of days on which thunder was heard per year for United States (*after W. H. Alexander*).

XII. DISTRIBUTION AND FREQUENCY OF THUNDER-STORMS

The seasonal and annual frequency of thunder-storms in different parts of the world has been determined by Brooks [734], whose distribution map for the whole year is shown in Figure 3. This map gives the percentage of days of the year on which thunder was heard in each region. Lines joining points with the same percentage are termed "isoceraunics." A map prepared by Alexander [728] for the United States is reproduced in Figure 4; on this the numbers represent the average number of days per year on which thunder-storms occur.

Such maps give no indication of the activities of thunder-storms in various regions or of the fraction of the flashes which pass to ground. This fraction, owing to the greater height of the storms, is much less in tropical and equatorial than in temperate regions.

Brooks estimates the number of thunder-storms occurring per annum over the whole Earth to be about 16 million. Taking the average duration of each to be one hour, he finds that there will, on the average, be 1,800 storms in progress at any one moment. He estimates the number of lightning-flashes occurring per sec to be about 100.

A diurnal variation of thunder-storm activity with universal (Greenwich) time has been deduced by Whipple [620] from these results.

XIII. LIGHTNING*

(1) COMPONENT STROKES OF THE LIGHTNING-DISCHARGE

Photographs taken with a camera in which the film or lens is moved show that many lightning-discharges are made up of a number of separate strokes. The interval between these strokes varies considerably but is of the order of one-fiftieth sec. A photograph of a single flash taken by Larsen [747] showed 40 distinct strokes at an average interval of 0.016 sec. Individual intervals varied from 0.0026 to 0.052 sec, and the total duration of the discharge was 0.624 sec. Many photographs of this kind have been taken by Walter [783] and others [747, 750, 779].

An explanation of the manner in which successive strokes develop along the same path has been based by Ollendorff [755] upon the volt-amp characteristic of the discharge-channel. Evidence that in many cases separate strokes arise from separate centers of charge within the thunder-cloud has recently been reported by Schonland.

It is generally observed that the first of the series of lightning-strokes which may compose a flash is by far the most energetic and is also the most heavily branched. Branches on the second subsequent strokes are unusual.

The duration of individual strokes varies considerably. Schmidt [762], using a visual method, found that the duration did not usually exceed 30 microseconds. D. J. Malan and H. Collens [770], using photographic recording, have found times up to 0.5 sec, and K. B. McEachron even longer ["J. Frank. Inst." **227,** 149].

(2) ELECTRICAL EFFECTS OF DIRECT STROKES

When an earthed conductor is struck by lightning, the passage of the current causes a very considerable potential difference to develop between the top of the conductor and the ground. Thus a conductor such as the metal mast supporting a power-line, carrying a current of 100,000 amp and with an effective impedance to Earth of 30 ohms, would develop a potential of 3×10^6 volts above or below zero, and arcing may take place to the insulated power-lines it supports. For this reason considerable attention has been paid by power-engineers to the characteristics of the direct stroke. *Potentials* of five million volts have been observed associated with traveling surges on power-lines by Pittman and Torok [758], while Brasch and Lange [732], using a wire stretched across an Alpine valley, obtained a potential of ten million volts. *Currents* passing down towers have been found to reach a maximum of the order of 60,000 amp, using a modern development of Pockels' [759] method of determining the residual magnetism in a ferromagnetic material at a known distance from the discharge [748]. Somewhat larger values, up to 250,000 amp, have been found by determining the potential drop across a portion of the tower with a device employing Lichtenberg figures on a photographic film, but some doubt attaches to the surge-impedance of the shunted section of the conductor. The *current-density* in the lightning-channel and the *diameter* of the conducting portion of the channel are very uncertain qualities [767]. Toepler [781] gives an upper limit of 20 cm to the diameter but points out that much smaller values are suggested by the holes sometimes made by the stroke in solid bodies. Fulgurites formed by the fusion of sand struck by lightning have a diameter of about five cm. Toepler estimates the current-density as 10,000 amp/cm; Biermans (see "Forschung und Technik," p. 234) and Petersen in laboratory experiments for the General Electric Company of Germany have found maximum current-densities for the spark-discharge of 5,000 and 10,000 amp/cm^2, respectively. The *time-variation* of the current in the discharge is also uncertain, for only a few oscillograms of lightning-surges have been taken close to the point where a power-line was struck. One reported on by Lewis and Foust [748] showed a rise to maximum current in five microseconds and a complete duration of about 100 microseconds. Accounts of recent progress in the study of the direct effects of lightning have been published by Goodlet [738], McEachron and McMorris [750], and Lewis and Foust [748]. Norinder [752] has determined the rate of change of current in the discharge by a method involving the effect of the change of magnetic linkage through a coil connected to an oscillograph, with results similar to those quoted above.

---

* Descriptions of the various types of natural lightning (ribbon, rocket, bead, forked, zigzag, streak, sheet, ball) are given in the handbook of the National Bureau of Standards, "Code for protection against lightning," Washington, 1933; see also Humphreys' "Physics of the air," Philadelphia, 1920, for a good general account.

(3) THE TIME-VARIATION OF CURRENT IN THE DISCHARGE

Although it was originally supposed that the lightning-discharge was oscillatory, several lines of investigation show that the main discharge is aperiodic. The evidence of the cathode-ray oscillograph applied to both near and very distant discharges (Sections I-4 and X) shows that the main effect of a distant lightning-discharge is a unidirectional pulse which rises to a maximum and then falls to zero. Neither the study of the current-time curve in a direct stroke (Section XIII-4) nor photographic recording of the luminosity-time curve reveals a reversal of the main discharge.

Simpson [777], applying the condition $R^2 < (4L/C)$ to the lightning-channel, finds it would be capable of oscillation if the resistance were less than one ohm per meter. Humphreys [496], on somewhat different assumptions, finds 0.2 ohm per meter for the critical resistance.

Ripples superimposed upon the main discharge without reversing its direction of flow have been observed (Sections I-4 and X), and these may be due to self-oscillation of the channel, as suggested by Simpson.

(4) THE MODE OF DEVELOPMENT OF THE DISCHARGE

A method of obtaining direct information as to the mode of development of the lightning-discharge has been described by Boys [730]. It consists in the use of a camera with a fixed plate and two lenses revolving in a circle at opposite ends of a diameter. The two pictures of the lightning-flash thus obtained show distortions, due to the motions of the lenses, which are in opposite directions. From a comparison of the two pictures and from knowledge of the velocities of the lenses, the direction and speed of the developing discharge can be deduced. The method has been used by Boys [730], Halliday [740], and Schonland, Collens, and Malan. The last-named workers [770] have shown that the development of a single stroke takes place in general in two stages. The first or leader-stage involves the downward movement of a luminous streamer from the cloud. This leader, in the case of the first stroke of a series, proceeds in steps of approximately 50 meters with pauses of duration about 10^{-4} sec between each. In the case of the second and subsequent strokes, the luminosity of the leader is similar to that which would be produced by a continuously moving dart 50 meters long and traveling at a velocity which varies from 2×10^8 to 4×10^9 cm/sec. Evidence of the existence of the leader to first strokes was originally given by Walter [in "Jahrb. Hamburg Wiss. Anstalten," **20** (1903)], using a single slow-moving camera.

The second or return stage of a stroke was found to occur when the leader arrived at the ground and took the form of a more intense flame-like upward-moving discharge, with an average velocity of 6×10^9 cm/sec.

The downward branching of the majority of the first strokes of a discharge was found to be formed during the downward passage of the first leader, the branches being subsequently more intensely illuminated in the return upward stroke.

These observations have been confirmed by Lloyd and others at the High-voltage Engineering Laboratory, at Pittsfield, Massachusetts [761], using a Boys camera with fixed lenses and moving film.

Theories of the development of the discharge have been put forward by Simpson [775], Dorsey [735], Schonland [766], Jehle [742], Rudenberg [761], Cravath and Loeb [734-*A*], and Ollendorff [754]. Schonland and Collens [770] identify the leader-process with a swarm of electrons propelled downward in the field of a negatively charged cloud-base, and the return-stroke with a neutralizing tongue of the kind suggested by Simpson [775]. On this view all processes in the discharge are electrical streamers, the leaders being negative streamers and the return-processes positive ones. All except the first leader-streamer travel along previously ionized channels.

The leader-process in the case of a discharge to ground lowers negative charge into the air, which charge is distributed over its channel and branches [770, 954]. In the return-stroke process this charge and that remaining on the cloud-center tapped by the leader are removed to earth.

Discharges taking place within the cloud do not appear to exhibit a return-stage.

CHAPTER XIII

BIBLIOGRAPHICAL NOTES AND SELECTED REFERENCES

H. D. Harradon

Department of Terrestrial Magnetism, Carnegie Institution of Washington

I. INTRODUCTION

The object of this bibliography is to indicate some of the more important contributions to the subjects of terrestrial magnetism and electricity which may be useful to those interested. So vast a literature has come into existence during the long period of development of geomagnetic and geoelectric research that only a small proportion of the whole can be listed here. Moreover, since these investigations extend over the whole Earth and have been conducted by different nations, many of the important papers are in languages other than English and, although this volume is intended primarily for American readers, a large number of these foreign publications must be included.

It has been thought best to indicate a few works pertaining to the early history of terrestrial magnetism, particularly reviews and surveys of the literature where extensive bibliographies and discussions may be found. The inaccessibility of the older contributions, valuable as they may be to the historian, makes the inclusion of a detailed list unjustified. However, in the items cited, sufficient references are given to satisfy any reader who desires to investigate the historical aspects of terrestrial magnetism.

The world-wide nature of geophysical research and the advisability of cooperation and coordination of effort have for many years engaged the attention of international scientific organizations. General progress is thus reflected in their deliberations and resolutions. Brief descriptions of these bodies, with respect to terrestrial magnetism and electricity, are therefore given, with mention of the meetings held and their reports.

A complete list of the publications containing the magnetic results obtained at all observatories, past and present, would exceed the limits of a bibliography of this kind. During the early years of work at observatories, terrestrial magnetism was often included under meteorological work and the results were more or less concealed in volumes of meteorological data; during more recent years, the tendency has been to publish the magnetic results by themselves, but as yet there is little uniformity in the publications of the various observatories although efforts to bring about this desired uniformity are being made by the International Association of Terrestrial Magnetism and Electricity. The publications, however, of certain observatories contain, in addition to observational data, extremely important discussions, as in the notable case of the Bombay Observatory, and an attempt has been made to include such publications in this list. As to the various observatories in operation, reference may be made to the lists of latest annual values at observatories published from time to time since 1907 by J. A. Fleming in the "Journal of Terrestrial Magnetism and Atmospheric Electricity" and in the "Transactions of the Meetings of the International Association of Terrestrial Magnetism and Electricity." The latest list is in the "Transactions of the Edinburgh Meeting" (Bull. No. 10, pp. 323–330, 1937). A manual containing a list of all magnetic and electric observatories, with descriptive data and annual values of magnetic results, is in preparation by the International Association of Terrestrial Magnetism and Electricity.

Lists of important papers on the rapidly expanding researches in cosmic radiation and on the ionosphere are included on account of their intimate connection with present geophysical investigations. Likewise, a list of publications, mostly of a general nature, dealing with geophysical prospecting, particularly by the magnetic and electric methods, is given.

In general, publications are preferably listed containing summaries of the subjects which they treat and particularly such papers as give detailed bibliographies of special papers for which there is not space for inclusion here. Indication is made in the cases of publications which contain valuable or extensive bibliographies.

II. CLASSIFICATION OF BIBLIOGRAPHY

For convenience of reference, the bibliography has been divided into the following general groups:

(*A*) Terrestrial magnetism:
  (*a*) Works pertaining to the history of terrestrial magnetism
  (*b*) General—(1) classical and reference works; (2) solar magnetism
  (*c*) Expeditions (chronologically arranged)
  (*d*) Popular addresses and essays of non-technical content
  (*e*) Instruments—(1) instruments and methods of measurement; (2) comparisons
  (*f*) Permanent field—(1) general; (2) magnetic surveys, charts, and tables; (3) observatories
  (*g*) Periodic variations (diurnal, lunar, annual, etc.) and magnetic activity
  (*h*) Secular variation
  (*i*) Magnetic disturbances, pulsations, solar and cosmical relations
  (*j*) Magnetic anomalies—(1) local magnetic anomalies; (2) magnetism of rocks, etc.
(*B*) Terrestrial electricity
  (*a*) General—(1) handbook articles, theoretical and descriptive papers; (2) observations

- (*b*) Instruments and methods of measurement
- (*c*) Potential-gradient and space-charge
- (*d*) Conductivity, ion-mobility, etc.
- (*e*) Air-earth current
- (*f*) Electricity of precipitation
- (*g*) Thunder-storms and lightning
- (*h*) Aurora
- (*i*) Earth-currents

(*C*) Geophysical prospecting—(*a*) general; (*b*) magnetic methods; (*c*) electric methods
(*D*) Ionosphere
(*E*) Cosmic radiation
(*F*) Radioactivity
(*G*) Ozone
(*H*) Miscellaneous

After this general bibliography had been completed, it was decided to expand it by the inclusion of all other references listed in the chapters of this volume, in order to eliminate duplication in printing. Many of the entries made to effect this are of more or less special nature—in some cases merely notes and in others only remotely bearing on terrestrial magnetism and electricity—and thus not appropriate in a general bibliography. A large proportion of these added references have been assembled at the end of the Bibliography under the classification "Miscellaneous" in groups corresponding to the classes of the general bibliography.

III. INTERNATIONAL BODIES

The first international conference on terrestrial magnetism, as far as the author can ascertain, took place at Cambridge, England, in 1845 during the meetings of the British Association for the Advancement of Science. The number who participated in this conference was considerable, particularly in view of the conditions of travel in those days. Among those present may be mentioned especially: Baron von Walterhausen, who had taken part in the magnetic observations of Gauss and Weber at Göttingen and had executed a magnetic survey of portions of Italy and Sicily; A. Kupffer, Director-General of the Magnetic Observatories of the Empire of Russia; C. Kreil, Director of the Meteorological and Magnetic Observatory at Prague; Baron von Senftenberg, founder of the Astronomical, Magnetic, and Meteorological Observatory of Senftenberg in Bohemia; Erman and Dove of the University of Berlin; and von Boguslawski of Breslau. On the list of British men of science invited to be present were the well-known names of Sir John Herschel, Lloyd, Airy, Broun, Scoresby, and Sir James Ross, who had recently returned from the Antarctic seas. Letters were received from Wilhelm Weber, Gauss, Lamont, Quetelet, von Humboldt, and others.

The principal question which this conference had to decide was whether "the combined system of British and foreign cooperation for the investigation of magnetic and meteorological phenomena, which had been five years in progress, must be broken up." One of the resolutions of this conference, expressing the sentiments which lie at the foundations of international geophysical progress today, was as follows: "That the cordial cooperation which has hitherto prevailed between the British and foreign magnetic and meteorological observatories having produced the most important results, and being considered by us as absolutely essential to the success of the great system of combined observation which has been undertaken, it is earnestly recommended that the same spirit of cooperation shall continue to prevail." For the detailed proceedings of this pioneer magnetic and meteorological congress, reference should be made to the Report of the Fifteenth Meeting, British Association for the Advancement of Science, Cambridge, 1845, pages 1–73 (1846).

Other international organizations which concern themselves with terrestrial magnetism and electricity and closely allied subjects are the following:

(1) International Union of Geodesy and Geophysics: Association (formerly Section) of Terrestrial Magnetism and Electricity

This Union and Association were founded in 1919. Ten bulletins have been published by the Association containing reports and transactions of the various assemblies, including Brussels, 1919 ["Organization, minutes, and proceedings," Bull. No. 1, 1919]; Rome, 1922 ["Transactions," Bull. No. 3, 1923]; Madrid, 1924 ["Transactions," Bull. No. 5, 1925]; Prague, 1927 ["Comptes rendus," Bull. No. 7, 1929]; Stockholm, 1930 ["Comptes rendus," Bull. No. 8, 1931]; Lisbon, 1933 ["Comptes rendus," Bull. No. 9, 1934]; Edinburgh, 1936 ["Transactions," Bull. No. 10, 1937]. The "Transactions" contain the proceedings and minutes of the meetings, reports of national committees and of special committees, comments on the agenda, and communications. This is the most important international organization for terrestrial magnetism and electricity at the present time.

Under the auspices of this Association is also published [Tome I, applying to 1930] the "Caractère magnétique numérique des jours."

(2) International Meteorological Organization (formerly International Meteorological Committee)

This Organization was established in 1872. At its Paris meeting in 1896, a Commission of Terrestrial Magnetism and Atmospheric Electricity was appointed which held meetings as follows: Paris, 1896; Bristol, 1898; Paris, 1900; Innsbruck, 1905; Berlin, 1910. At the Berlin meeting, it was decided to divide the Commission into two commissions, one for Terrestrial Magnetism and the other for Atmospheric Electricity. After the war, however, in 1919, the Commission of Terrestrial Magnetism and Atmospheric Electricity was reorganized by the Conference of Directors and completed in 1921 by the International Meteorological Organization. Since that time meetings have been held as follows: Utrecht, 1923; Zürich, 1926; Copenhagen, 1929; Innsbruck, 1931; Warsaw, 1935.

Under the auspices of the Commission of Terrestrial Magnetism and Atmospheric Electricity was published the "Caractère magnétique de chaque jour" from its inception in 1906 until 1937, when the expense of publication was assumed by the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics.

At the Seventh Conference of (Meteorological) Directors held at Copenhagen in 1929, the International Commission for the Second Polar Year 1932–33 was instituted. Three reports have been issued by the Commission, namely, "Procès-verbaux des séances" at Leningrad (1930), at Innsbruck (1931), and at Copenhagen (1933) [Secrétariat de l'Organisation Météorologique Internationale, Nos. 6, 10, and 16]. The first International Polar Commission (1882–83) was formed in 1879 and held its first conference during that year in Hamburg. Its organization and history are covered in "Communications from the International Polar Commission," edited by H. Wild [Nos. 1–110, 334 pp., St. Petersburg, Imperial Academy of Sciences (1881–84)].

Under the auspices of the International Meteorological Committee was published the "Internationaler meteorologischer Kodex" [Berlin, "Veröff. met. Inst.," No. 242, 103 pp. (1911)], compiled by G. Hellmann and H. H. Hildebrandsson for the Committee. This second edition supersedes the first edition of 1907.

(3) INTERNATIONAL COUNCIL OF SCIENTIFIC UNIONS (FORMERLY INTERNATIONAL RESEARCH COUNCIL)

Under the auspices of this International Council, its Commission Appointed to Further the Study of Solar and Terrestrial Relationships has published four reports, issued in 1926, 1929, 1931, and 1936, respectively.

(4) INTERNATIONAL ASTRONOMICAL UNION

The International Astronomical Union is responsible for the publication of "Character-figures of solar phenomena." Thus far, those published by the Eidgenössische Sternwarte, Zürich, include: Volume I, 1923–28 (1932); II, 1917–22 (1933); III, 1928–33 (1934). This publication is now issued in the form of quarterly bulletins; volume IV, giving data from 1934, is now in progress.

IV. AMERICAN GEOPHYSICAL UNION

The American Geophysical Union was established in 1919 as the American Committee of the International Union of Geodesy and Geophysics, its Executive Committee being the Committee on Geophysics of the National Research Council. Annual assemblies of the Union and annual meetings of its seven sections, at which scientific papers are presented and discussed, have been held since its establishment. The "Transactions" of these annual assemblies and meetings through the ninth were published in the Bulletin series of the National Research Council as follows: Second, 1921, Bull. No. 17; fourth, 1923, Bull. No. 41; sixth, 1925, Bull. No. 53; seventh, 1926, Bull. No. 56; eighth, 1927, Bull. No. 61; and ninth, 1928, Bull. No. 68. The "Transactions" of the tenth and eleventh annual meetings held in 1929 and 1930 were published in one volume in June, 1930, and those of the twelfth (1931), thirteenth (1932), fourteenth (1933), fifteenth (1934), sixteenth (1935), seventeenth (1936), eighteenth (1937), and nineteenth (1938) annual meetings were published in the same year in which the meetings were held in the series of Miscellaneous Publications of the National Research Council. At the first, third, and fifth annual meetings, held in 1920, 1922, and 1924, respectively, no scientific papers were presented and the transactions for these were not printed but were mimeographed for limited distribution only.

The scientific papers presented in the Section of Terrestrial Magnetism and Electricity are printed in full or in abstract in the various volumes of the "Transactions" and present from year to year the activity and progress in these branches in America.

V. PUBLICATIONS OF OBSERVATORIES AND INSTITUTIONS

There is at present no uniform practice in the form or manner of publishing magnetic data obtained at observatories, although this has been a subject of discussion at international scientific meetings. In many instances, terrestrial magnetism was originally included in the program of meteorological observatories, just as the Commission of Terrestrial Magnetism and Atmospheric Electricity is still a part of the International Meteorological Organization. It thus happens that the magnetic results are still often published with the meteorological data, as, for example, in the "Observatories' Year Book of the Meteorological Office," London, from which the excellent form of presenting the magnetic data has been taken as a model by numerous magnetic observatories.

No attempt has been made to list all the publications of observatories containing magnetic and electric results. There are, however, a number of observatories and institutions which publish, in addition to observational data, summaries and discussions of magnetic results. Although of great value, these publications are not always readily accessible, owing to their limited distribution. Some of the more important series of publications of this type by observatories and institutions are given below.

Researches of the Department of Terrestrial Magnetism, Carnegie Institution of Washington, Publication No. 175.—Six volumes have appeared (1912–27) of which the first two are already out of print. Volumes I, II, IV, and VI contain the results of all magnetic observations made on land (almost wholly outside the United States) by the Department of Terrestrial Magnetism during 1905–10, 1911–13, 1914–20, and 1921–26, respectively. Volumes III and V present the final results of all magnetic and electric observations made at sea during 1905–21; the first gives the results obtained on the chartered vessel, the *Galilee*, during 1905–08, and on the specially constructed vessel, the *Carnegie*, during 1909–16 (including preliminary values only for 1915–16) and the second the results obtained on the *Carnegie* during 1915–21. Descriptions of the types of instruments used for the work on land and sea are given, together with accounts of the development, design, and construction of new magnetic instruments of light and portable types. The discussions of the general methods of the magnetic and astronomical field-work, on both land and sea, include, besides general theory and details, specimens of records, computations, and determinations of constants and corrections.

Volumes II, III, IV, and V contain also special reports and discussions of the magnetic data collected, atmospheric-electric results obtained (particularly at sea), and various other observational and investigational work done.

Volume VI consists of two sections, the first presenting the magnetic results on land for the years 1921–26 and the second section containing the report of magnetic, atmospheric-electric, and auroral observations made on the *Maud* Expedition, 1918–25.

Volume VII, which is ready for the printer, will contain the observatory magnetic results for Watheroo, 1919–36; Huancayo, 1922–36; and special reports.

Publications of the United States Coast and Geodetic Survey.—The Annual Reports of the United States Coast and Geodetic Survey were published in a separate Survey edition 1851–1911 in quarto volumes. The appendices of these reports treating scientific and professional subjects contained almost all of the material of that character published by the Survey and included many important monographs pertaining to terrestrial magnetism; these appendices were also printed as separates when the demand warranted it. Subsequent to 1911 the annual reports were issued in smaller format and the scientific material previously issued as appendices was published in special or serial publications. The first special publication, however, was published in 1898, and dealt with a subject from terrestrial magnetism, namely, "Magnetic ranges for determining the deviation of the compass, with short explanations of how to find the deviation and error of the compass" by J. C. Gilmore. The object of the series of special publications was to provide for special subjects which could not conveniently be included in the annual reports. At the present time these series include, among other matter, the results of magnetic observations made by the Survey in the field, the observations made at the Survey's magnetic observatories, and monographs dealing with special aspects of terrestrial magnetism.

A detailed list and catalogue of the publications issued 1816–1902, with a supplement covering the period January, 1903, to August, 1908, was published by the Survey in 1908; in this catalogue are listed the titles of all the appendices appearing in the period designated, often with explanatory notes. Later publications are listed annually in the "Lists of publications of the Department of Commerce."

Among the serial publications of the Survey should be mentioned the "United States magnetic tables and charts" which is issued for various epochs. The last of these publications was Serial No. 453, applying to 1925, superseding Special Publication No. 44 for 1915. This valuable publication contains: Observed values of the magnetic declination, dip, and horizontal intensity for all places in the United States at which reliable observations have been made, together with corresponding reduced values for January 1, 1925; tables giving the results of observations at repeat-stations occupied between January, 1917, and December, 1928; also tables giving the changes of the magnetic elements with time; and magnetic charts showing graphically by isomagnetic lines the general distribution of the declination, dip, horizontal intensity, and vertical intensity in the United States at the beginning of 1925. The corresponding tables and charts for 1935 appeared in 1938 as Serial No. 602.

Annales de l'Institut de Physique du Globe de l'Université de Paris et du Bureau Central de Magnétisme Terrestre.—Published annually beginning 1923 (Paris, Les Presses Universitaires de France). These contain the results of magnetic observations made at the Val Joyeux and Nantes observatories beginning with the year 1915 in continuation of the results previously appearing in the Annales du Bureau Central Météorologique, the publication of which was retarded by the World War. In addition to the annual magnetic results at observatories, reports on magnetic field-work in France and in her colonies, as well as contributions on atmospheric electricity, solar radiation, seismology, and other geophysical subjects are included. Thus in volume XV (1937) is published a detailed contribution by J. Rothé on the study of magnetic anomalies (pp. 1–110).

Archiv des Erdmagnetismus, herausgegeben von Adolf Schmidt: Eine Sammlung der wichtigsten Ergebnisse erdmagnetischer Beobachtungen in *einheitlicher Darstellung.*—The first volume of four numbers (Potsdam, 1903–26) contains tables of diurnal variation at a large number of observatories, its dependence on solar activity, etc. The last three numbers were issued in the Abhandlungen des Preussischen Meteorologischen Instituts. Number 5 [Abh. **8,** No. 2 (1925)] contains: "Allgemeine Formeln zur Vereinfachung häufig wiederholter Potentialrechnungen durch Benutzung fester Stationgruppen" by Adolf Schmidt; "Versuch einer analytischen Darstellung des Verlaufs der Säkular-Variation im Zeitraum 1902–1920" by J. Bartels; "Erdmagnetische Aktivität" by J. Bartels. Number 6 [Abh. **8,** No. 11 (1927)] contains: "Karten der Verteilung des Erdmagnetismus und seiner örtlichen Störungen in Europa" by A. Nippoldt. Number 7 [Abh. **9,** No. 1 (1928)] contains: "Die Mondperiode der erdmagnetischen Vertikalkomponente nach den Registrierungen des Potsdamer Magnetographen in den Jahren 1891–1905" by O. Venske; "Der Einfluss des Mondes auf die erdmagnetischen Elemente in Potsdam und Seddin während der Jahre 1905–1924" by Adolf Schmidt.

Magnetic observations made at the Government Observatory, Bombay, for the period 1846 *to* 1905 *and their discussion, by N. A. F. Moos.*—This two-volume work (Bombay, 1910) contains the Colaba magnetic data extending over 60 years, which with their elaborate discussion forms a most important contribution to terrestrial magnetism. Part I gives the magnetic data and describes the instruments; part II discusses the data and phenomenon. Subsequent volumes for 1906–10, 1911–15, 1916–20 and the later annual volumes contain magnetic data obtained at Alibag, the new site to which the magnetic work at Bombay was transferred in 1904 after the electrification of the tram-lines in the City of Bombay had rendered the station at Colaba unsuitable.

Communications magnétiques, etc., publiées par l'Institut Météorologique Danois, Copenhagen.—The first issue appeared in 1927. In this series are published memoirs and extracts from the archives of the Rude Skov and Godhavn observatories. Eighteen communications have been published up to July, 1937.

Berichte über die Tätigkeit des Preussischen Meteorologischen Instituts. Published annually until 1933 in the "Veröffentlichungen" of that Institute. The appendices contain many valuable papers by members of the Institute dealing with terrestrial magnetism and electricity.

Astronomische Mitteilungen.—This publication, founded by R. Wolf, is published by W. Brunner of the Eidgenössische Sternwarte at Zürich. It is issued irregularly—No. 137 appeared in 1939. It contains statistics of sunspot-numbers and other solar phenomena based upon observations at Zürich and other collaborating observatories. The provisional relative sunspot-numbers (based only on observations at Zürich Observatory and its station at Arosa) are regularly published in the "Journal of Terrestrial Magnetism and Atmospheric Electricity," "Meteorologische Zeitschrift," and elsewhere. The final relative sunspot-numbers are also published annually in the first-named journal.

Jordmagnetiska Publikationer.—Published at irregular intervals by Kungl. Sjökarteverket, Stockholm. First number appeared in 1919, 12 numbers having been issued by early 1939. These publications deal primarily with results of magnetic researches in Sweden and the surrounding waters.

Caractère magnétique de chaque jour.—Compiled by the Royal Meteorological Institute of the Netherlands and published under the auspices of the Commission of Terrestrial Magnetism and Atmospheric Electricity of the International Meteorological Organization during 1906–36. From 1937 this publication has been issued under the auspices of the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics. These figures are also reviewed in the "Journal of Terrestrial Magnetism and Atmospheric Electricity" [from **13**, 36–37 (1908)] and in the "Meteorologische Zeitschrift" [from **28,** 130 (1911), beginning with the year 1909].

Caractère magnétique numérique des jours.—Compiled and published by the Royal Meteorological Institute of the Netherlands under the auspices of the Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics. Volume 1, January to December, 1930, 40 pp., issued in 1932, to volume 28, July to September, 1938, 25 pp., in 1939. A supplement of 85 pages giving the numerical magnetic character-numbers of days during the International Polar Year 1932–33 was issued in 1937.

Prace Observatorjum Magnetycznego w Swidrze (*Travaux de l'observatoire magnétique à Swider*).—This series contains, in addition to the results of observations made at the Swider Magnetic Observatory, accounts and results of magnetic survey of Poland, and isogonic charts of Poland for 1927 and 1935. It is published in Polish and French at irregular intervals by St. Kalinowski; numbers 1 to 9 were issued during 1919–37.

Long series of results at observatories.—Among the longer series of results at observatories are the following:

Batavia: "Observations made at the Royal Magnetical and Meteorological Observatory at Batavia"; series began with 1866; summaries for 1866–1916 given in **39** (1916); for 1866–1920 in **43** (1920); and for 1866–1925 in **48** (1925).

Bombay: Results go back to 1846 (see above).

Greenwich: "Magnetic and meteorological observations made at the Royal Observatory, Greenwich"; series began with 1840.

Potsdam, Seddin, Niemegk: "Ergebnisse der magnetischen Beobachtungen in Potsdam (und Seddin)," Adolf-Schmidt-Observatorium, Niemegk (since 1932); Geophysikalisches Institut, Potsdam (since 1936); series began in 1890, appearing in "Veröffentlichungen des Preuss. Meteorologischen Instituts," Berlin. Instrumental and theoretical questions are discussed in accompanying text. An index by A. Nippoldt appeared in the "Ergebnisse" for 1927. Summarizations in "Ergänzungsband zu den Jahren 1892–1900" by W. Brückmann ["Veröff.," No. 232, 100 pp. (1911)] and "Ergebnisse der magnetischen Beobachtungen in Potsdam und Seddin in den Jahren 1900–1910" by Adolf Schmidt ["Veröff.," No. 289, 52 + 40 pp. 1916)].

London, Meteorological Office: Lerwick, Aberdeen, Eskdalemuir, Valentia, Kew: The "Observatories' Year Book," comprising the meteorological and geophysical results obtained from autographic records and eye observations at the observatories at Lerwick, Aberdeen, Eskdalemuir, Valentia, and Kew, and results of soundings of the upper atmosphere by means of registering balloons, first appeared in 1922. It is in continuation of the former British "Meteorological and Magnetic Year Book," parts II and IV, which, beginning in 1911, presented in extended form the tables and summaries giving the results of observations in terrestrial magnetism and atmospheric electricity which had been included in the "Reports" of the Committee of Management of the Kew Observatory from 1842 to 1910.

United States Coast and Geodetic Survey: Cheltenham, Sitka, San Juan, Tucson, Honolulu: "Results of observations made at the United States Coast and Geodetic Survey magnetic observatories"—Cheltenham, Maryland (began 1901); Sitka, Alaska (began 1902); San Juan, formerly at Vieques, Puerto Rico (began 1903); Tucson, Arizona (began 1909); Honolulu, Hawaii (began 1902); Baldwin, Kansas (1901–09).

Rude Skov (Copenhagen) and Godhavn: The results for Rude Skov, Denmark (since 1906), and Godhavn, Greenland, are published in "Magnetisk Aarbog" by Det Danske Meteorologiske Institut, Copenhagen.

De Bilt: The results for De Bilt of Koninklijk Nederlandsch Meteorologisch Instituut are published in its "Jaarboek, B. Aardmagnetisme." The Institute was founded February 1, 1854, at Utrecht and was transferred in 1897 to De Bilt. Magnetic observations were begun at Utrecht in 1860; from January 1, 1899, they were made at DeBilt until 1938, when the service was transferred to Witteveen near the German border.

VI. SCIENTIFIC JOURNALS AND MEMOIRS

Terrestrial Magnetism and Atmospheric Electricity.—This international quarterly journal was founded in 1896 by the late Dr. Louis A. Bauer and is now (1939) in its forty-fourth volume (obtainable from the Johns Hopkins Press, Baltimore, Maryland). It contains original contributions to all aspects of terrestrial magnetism and electricity as well as reviews, notes, and an annotated bibliography. Principal magnetic storms and provisional sunspot-numbers appear regularly in each number. It is the oldest and practically the only journal devoted exclusively to these subjects.

Zeitschrift für Geophysik.—This journal is published by the Verlag von Friedr. Vieweg und Sohn, Braunschweig, being the organ of the German Geophysical Society. It contains not only articles on terrestrial magnetism and electricity but also on seismology, gravity, and other geophysical subjects. Volume 1 was published in 1925.

The Geophysical Magazine.—Published by the Central Meteorological Observatory, Tokyo, Japan, this magazine is devoted to geophysics and includes terrestrial magnetism and atmospheric electricity, although perhaps the majority of the papers are on meteorological and seismological subjects. The object of the magazine is thus stated by the editor: "Until now most of the papers published by the members of our Weather Service have remained quite unnoticed by our European colleagues, though they will be of some interest to them, simply because these papers are written in the language (Japanese) not easily intelligible to occidental readers. The launching of this new journal is to remedy this lamentable defect and to help better understanding with each other." The first issue appeared in July, 1926, and the eleventh volume was in progress in 1937.

Gerlands Beiträge zur Geophysik.—This journal was founded in 1887 by G. Gerland to contain contributions from the Geographical Seminar of the Strasburg University. Publication was suspended owing to the World War but in 1926 was resumed with volume 15 under the editorship of V. Conrad of Vienna and issued by the Akademische Verlagsgesellschaft, Leipzig. These "Beiträge" cover the whole field of geophysics. In 1931, however, appeared the first number of "Ergänzungshefte für angewandten Geophysik" which were to contain articles on geophysical prospecting. Again beginning with volume 5, number 4 (1933), the name of the "Ergänzungshefte" was changed to "Beiträge zur angewandten Geophysik." This supplement has now concluded its seventh volume, whereas the fifty-fourth volume of the "Beiträge zur Geophysik" is now in progress (1939). This important publication, together with its supplement, contains a number of very important contributions to terrestrial magnetism and electricity. Beginning with volume 54, number 1, which appeared in 1939, this journal is being published by a joint committee consisting of J. Bartels (Berlin), A. Defant (Berlin), H. Lettau (Leipzig), and L. Weickmann (Leipzig). In 1931, the first number of another important series of supplementary volumes to the "Beiträge zur Geophysik" appeared under the title "Ergebnisse der kosmischen Physik," edited by V. Conrad and L. Weickmann. Four volumes of these "Ergebnisse" have been published to date (1939). This series contains detailed summaries of the present status of our knowledge of various geophysical subjects and is a valuable reference for those working in cosmical physics.

Sitzungsberichte der Akademie der Wissenschaften in Wien, Mathem.-naturw. Klasse.—This periodical is now in its one hundred forty-seventh volume. It includes a large number of papers dealing with atmospheric-electric research in Austria, emanating chiefly from the school of Franz Exner and its successors. Most of these contributions were also issued as separates under the general title of "Beiträge zur Kentnis der atmosphärischen Elektrizität," the first number appearing in 1899. At the end of 1931, 73 numbers of this important collection had been issued; many of these are listed in this bibliography under the section on "Atmospheric electricity."

Information Book on Terrestrial Magnetism and Atmospheric Electricity. This series is published by the Central Magnetic Observatory, Slutzk, near Leningrad, U.S.S.R. The first issue appeared in 1935, and publication has been continued at the rate of about one number per annum since that time. Its object is to furnish information as completely and promptly as possible concerning activity in terrestrial magnetism and electricity both in the U.S.S.R. and abroad through summaries of researches, abstracts of papers, notes, etc. As it is intended primarily for Russians, it is almost entirely in the Russian language.

Other journals and magazines in which articles dealing with terrestrial magnetism and electricity are frequently published, are as follows:

Annales de physique du globe de la France d'outre-mer (paraissant tous les deux mois. Paris, Larose, éditeur).—Volume 1 published in 1934, volume 6 in progress (1939).

Geophysical Memoirs (London, Meteorological Office).—These Memoirs are published irregularly; nine volumes were issued during 1912–39.

Geofysiske Publikasjoner (Utgitt av det Norske Videnskaps-Akademi, Oslo).—Eleven volumes were issued during 1921–37; they contain important memoirs on the aurora.

Geophysics, A journal of general and applied geophysics (Houston, Texas).—Volumes 1, 2, and 3 for 1936–38 have been published by the Society of Exploration Geophysicists (formerly the Society of Petroleum Geophysicists), and volume 4 is in progress (1939).

Japanese Journal of Astronomy and Geophysics (Tokyo).—Published by the National Research Council of Japan; volume 15 for 1938 is in progress.

Meteorologische Zeitschrift (Braunschweig, Friedr. Vieweg und Sohn).—This is the organ of the Österreichische Gesellschaft für Meteorologie and the Deutsche Meteorologische Gesellschaft. Volumes 1 to 55 were published during 1884 to 1938; volume 56 is in progress (1939).

VII. BIBLIOGRAPHIES AND ABSTRACTS

Zentralblatt für Geophysik, Meteorologie, und Geodäsie (Berlin, Julius Springer).—Continuation from 1937 (vol. 1) as a separate journal of section entitled "Geophysik" heretofore published in "Zentralblatt für Mathematik und ihre Gränzgebiete." Abstracts in German, English, and French cover the whole field of geophysics.

Physikalische Berichte (Braunschweig, Vieweg).—Continuation of "Fortschritte der Physik," "Halbmonatlicher Literaturverzeichnis," and "Beiblätter zu den Annalen der Physik." Published, beginning with volume 1 for 1920, by the Deutsche Physikalische Gesellschaft and Deutsche Gesellschaft für Technische Physik. Twenty-four issues per annum. About eight issues per volume contain "Geophysikalische Berichte" which are also issued with the various numbers of "Zeitschrift für Geophysik."

Geophysical Abstracts (Washington, D. C.).—Numbers 1 to 86 (May, 1929, to June, 1936) were published monthly in mimeographed form by the United States Bureau of Mines (Department of Commerce). Numbers 87–92 appeared in 1937 and 1938 as Geological Survey Bulletins 887, 895-*A*, *B*, *C*, *D*, and 909-*A*, covering the period July, 1936, to March, 1938 Abstracts of current articles and publications dealing with applied geophysics and brief notes on pertinent domestic and foreign patents are also included.

Berichte über die Fortschritte unserer Kentnisse vom Magnetismus der Erde (Gotha, Justus Perthes).—Numbers I to VII by K. Schering, Numbers VIII to IX by J. Bartels, cover the literature from 1830–1929 and are very useful for reference. They appear in the following volumes of the "Geographisches Jahrbuch": 13, 15, 17, 20, 23, 28, 36, 40, and 44.

Annotated Bibliography of Economic Geology (Lancaster, Pennsylvania).—Published semiannually by the Economic Geology Publishing Co., Urbana, Illinois, this bibliography is prepared under the auspices of the Society of Economic Geologists. Volume 1 (1929) covers the literature for 1928. Titles and abstracts in English. In a section entitled "Geophysical Prospecting" abstracts of literature on the various methods of applied geophysics are given.

List of recent publications.—Published quarterly in the "Journal of Terrestrial Magnetism and Atmospheric Electricity," this includes bibliography of current literature, grouped under the headings Terrestrial and Cosmical Magnetism, Terrestrial and Cosmical Electricity, and Miscellaneous.

Repertorium der deutschen Meteorologie; Leistungen der Deutschen in Schriften, Erfindungen und Beobachtungen auf dem Gebiete der Meteorologie und des Erdmagnetismus von den ältesten Zeiten bis zum Schlusse des

Jahres 1881 [Leipzig, W. Engelmann, xxii + 995 pp. (1883)].—This compilation, edited by G. Hellmann, contains notices of all German works on terrestrial magnetism up to 1881.

Bibliography of Meteorological Literature.—Prepared by the Royal Meteorological Society with the collaboration of the Meteorological Office and published by the Royal Meteorological Society, this bibliography replaces the one previously published in the "Quarterly Journal of the Royal Meteorological Society." The first issue covered the period from September, 1920, to June, 1921, and the later ones were continued in six-monthly parts. It contains sections on terrestrial magnetism, electrical phenomena, etc.

(1) ABBREVIATIONS

In referring to periodicals, the usage in the "International Catalogue of Scientific Literature," which was published for the International Council by the Royal Society of London, has served as a basis. Since, however, no annual issues of the "International Catalogue" have appeared since that applying to the year 1914, several abbreviations have necessarily been introduced on account of the large number of scientific journals which have been established since that time. In nearly all cases the references will be readily understood from the abbreviations so that it is not considered necessary to explain each case in detail. Abbreviations of obscure sources have been amplified to render them more easily intelligible. The number of the volume (Jahrgang, Band, année, etc.) has been set in bold-face type, and the date of publication has been placed at the end in parentheses. In the case of well-known periodicals, the place of publication has been omitted as is the custom in nearly all scientific journals as well as in the other volumes of this series on "Physics of the Earth."

(*A*) TERRESTRIAL MAGNETISM

(*a*) *Works pertaining to the history of terrestrial magnetism*

The early history and progressive development of the science of terrestrial magnetism present a fascinating field for study and have been the object of much investigation by eminent scholars. Many of the earliest documents, however, are not readily accessible and, as interest in them is chiefly from the viewpoint of history, reference is made here principally to publications in which they are described and discussed, thus providing a good starting point for those who may desire to delve further into this field of research.

[1] Bauer, L. A. The earliest values of the magnetic declination. Terr. Mag., **13**, 97–104 (1908).

[2] Benjamin, P. A history of electricity (the intellectual rise of electricity) from antiquity to the days of Benjamin Franklin. New York, John Wiley & Sons, Inc., 611 pp. (1898). [First published in London, 1895. Contains a careful survey of the early history of terrestrial magnetism.]

[3] Bertelli, T. Sopra Pietro Peregrino di Maricourt e la sua epistola De Magnete. Boll. bibliogr. st. sc. mat., Roma, **1**, 1–32, 65–69, 101–139, 319–420 (1868). [This is only one of the valuable contributions of this scholar to the early history of terrestrial magnetism. For full list of his papers, reference may be made to the bibliography accompanying article by A. Crichton Mitchell in Terr. Mag., **37**, 138 (1932).]

[4] Boehm, E. Zur Geschichte des Erdmagnetismus. Hamburg, Realschule in Eilbeck, 40 pp. (1910). [Wissenschaftliche Beilage zum Bericht über das Schuljahr 1909/10.]

[5] Busch, W. Die Entwicklung des Schiffskompasses in Sage und Geschichte. Ann. Hydrogr., **54**, 120–126, 169–174 (1926).

[6] Crichton Mitchell, A. Chapters in the history of terrestrial magnetism. Terr. Mag., **37**, 105–146 (1932); **42**, 241–280 (1937); **44**, 77–80 (1939). [Chapter I, On the directive property of a magnet in the Earth's field and the origin of the nautical compass; Chapter II, The discovery of the magnetic declination; Chapter III, The discovery of the magnetic inclination. Comprehensive discussion based on long study of the subjects. Contains very extensive annotated bibliography of early works.]

[7] Günther, S. Johannes Kepler und der tellurisch-kosmische Magnetismus. Wien, Geographische Abhandlungen herausgegeben von A. Penck, **3**, Heft 2, 71 pp. (1888). [The first chapter, pp. 1–18, is devoted to the early history of terrestrial magnetism, with valuable references and comments in the footnotes. The two remaining chapters are concerned with Kepler's studies of the terrestrial-magnetic elements and of the position of the north pole, and with his theory of the magnetic planetary axes and of universal attraction.]

[8] Heathcote, N. H. de V. Christopher Columbus and the discovery of magnetic variation. Sci. Prog., **27**, 82–103 (1932).

[9] Hellmann, G. Die Anfänge der magnetischen Beobachtungen. Zs. Ges. Erdk., **32**, Heft 2, 27 pp. (1897). [A translation by Mrs. L. A. Bauer, under the title "The beginnings of magnetic observations," appeared in Terr. Mag., **4**, 73–86 (1899).]

[10] Hellmann, G. Über die Kenntnis der magnetischen Deklination vor Christoph Columbus. Met. Zs., **23**, 145–149 (1906). [Discussion of part played by early sun-dials provided with compass-needles in the discovery of the declination, with plate showing the earliest one known which dates from 1451.]

[11] Lippmann, E. O. von. Geschichte der Magnetnadel bis zur Erfindung des Kompasses (gegen 1300). Berlin, Julius Springer, vi + 49 pp. (1932). [Quellen und Studien zur Geschichte der Naturwissenschaften und der Medizin, **3**, Heft 1.]

[12] Schott, C. A. The value of the "Arcano del Mare" with reference to our knowledge of the magnetic declination in the earlier part of the seventeenth century. Washington, D. C., U. S. Coast Geod. Surv., Bull. No. 5, 25–28, 2 maps (1888). Also App. 6, rep. for 1888. [The author states his opinion of this early elaborate nautical work (Florence, 1646 and 1647) as follows: "Upon the whole, the scrutiny of the work left an impression favorable to its reliability, and if the omissions of observers' names and dates detract much from its value, it nevertheless fills a gap in a period of which our information has hitherto been most scanty and unreliable."]

[13] Schütz, E. H. Die Lehre von dem Wesen und den Wanderungen der magnetischen Pole der Erde. Ein Beitrag zur Geschichte der Geophysik. Berlin, Dietrich Reimer, xii + 76 pp., 4 pls. (1902).

[14] Thompson, S. P. William Gilbert, and terrestrial magnetism in the time of Queen Elizabeth. London, Charles Whittingham and Co., 16 pp. (1903). [Discourse delivered at meeting of Royal Geographical Society, March 23, 1903.]

[15] Urbanitzky, A. von. Elektricität und Magnetismus im Alterthume. Wien, A. Hartleben's Verlag, xiv + 284 pp. (1887). [Elektro-technische Bibliothek, **34.** Early history of magnetism, compass, amber, aurora, lightning, etc., is discussed.]

[16] Wehner, H. Über die Kenntnis der magnetischen Nordweisung im frühen Mittelalter. Berlin, Weltall, Heft 18–20, 20 pp. (1905). [Treats of the question of the orientation of churches in the Middle Ages. See also Nippoldt, Ein Beitrag zur Frage der Ausrichtung der Kirchenachsen mit dem Magneten, Arch. Ges. Naturw. Techn., **7,** 109–114, 236–244 (1916).]

[17] Winter, H. Seit wann ist die Missweisung bekannt? Ann. Hydrogr., **63,** 352–363 (1935).

[18] Wolkenhauer, A. Beiträge zur Geschichte der Kartographie und Nautik des 15. bis 17. Jahrhunderts. Inaug. Diss., Göttingen (München, F. Straub), 79 pp., 12 figs. (1904). [The principal subjects treated in this dissertation are: The knowledge of the magnetic declination before Columbus; sun-compasses and the knowledge of the declination; the displacement of the needle in ship-compasses. The writer maintains that the magnetic declination was known from the use of sun-compasses (that is, sun-dials provided with compass-needles) on land before its discovery by Columbus at sea. This matter is discussed in detail by L. A. Bauer in his article "The earliest values of the magnetic declination," Terr. Mag., **13,** 97–104 (1908).]

[19] Wolkenhauer, A. Der Schiffskompass im 16. Jahrhundert und die Ausgleichung der magnetischen Deklination. Ann. Hydrogr., **33,** 29–37 (1905).

(*b*) *General*

(1) Classical and reference works

[20] Airy, G. B. A treatise on magnetism: designed for the use of students in the University. London, Macmillan & Co., Ltd., xv + 220 pp. (1870).

[21] Angenheister, G. Das Magnetfeld der Erde und der Sonne. Göttingen, Nachr. Ges. Wiss., 229–236 (1924).

[22] Angenheister, G. Erdmagnetismus. Handbuch der Physik, herausgegeben von H. Geiger und K. Scheel, **15,** 271–320 (1927).

[23] Angenheister, G., and J. Bartels. Das Magnetfeld der Erde. Handbuch der Experimentalphysik, herausgegeben von W. Wien und F. Harms, **25,** I, 525–684 (1928). [An authoritative reference-work. It is divided into four chapters, namely: Instruments and methods (Angenheister); Permanent field and secular variation (Bartels); Periodical variations, activity (Bartels); Magnetic disturbances (Angenheister).]

[24] Bauer, L. A. Principal facts of the Earth's magnetism and methods of determining the true meridian and the magnetic declination. (Reprinted from United States magnetic-declination tables and isogonic charts for 1902.) Washington, D. C., U. S. Coast Geod. Surv., 100 pp., illus. (1902). Reprinted, with slight changes, 1909, 1914, and 1919. [This pamphlet contains a concise account of the early history of the compass and the science of terrestrial magnetism. Other subjects treated are: The variations (secular, diurnal, annual, etc.) of the Earth's magnetism; magnetic observatories, magnetic charts and surveys; the Earth's magnetic poles and magnetic moment; and the determination of the true meridian

and the magnetic declination. The publication is now out of print and has been superseded by "The Earth's magnetism" by D. L. Hazard.]

[25] Chapman, S. Theories of terrestrial and solar magnetism. Dictionary of Applied Physics, edited by Sir Richard Glazebrook, **2,** 543–561 (1922).

[26] Chapman, S. The Earth's magnetism. London, Methuen & Co., Ltd., xi + 116 pp. (1936).

[27] Chapman, S., and J. Bartels. Geomagnetism. Oxford University Press (in press).

[28] Chree, C. Terrestrial magnetism. Encyclopaedia Britannica, 11th ed., **17,** 353–385 (1911). [See corresponding article in 14th ed.]

[29] Chree, C. Studies in terrestrial magnetism. London, Macmillan & Co., Ltd., xii + 206 pp. (1912). [A connected account of the author's original work in terrestrial magnetism. The subjects discussed are: Magnetic records; secular change; non-cyclic change; diurnal inequality on quiet and disturbed days; Fourier coefficients; annual variation; absolute daily range; antarctic magnetic results; magnetic storms; sudden commencements; comparison of arctic and antarctic disturbances; sunspots and terrestrial magnetism; Wolf's sunspot-formula; nature of sunspot-relationship; and general conclusions. Not a general reference-book.]

[30] Gauss, C. F. Allgemeine Theorie des Erdmagnetismus. Resultate aus den Beobachtungen des magnetischen Vereins im Jahre 1838, pp. 1–57. Herausgegeben von C. F. Gauss und W. Weber. Leipzig (1839). [Republished in Gauss, Werke, **5,** 119–180, Göttingen, Kgl. Ges. Wiss. (1877). English translation by Mrs. Sabine, revised by Sir John Herschel, in Scientific Memoirs, edited by Richard Taylor, **2,** 184–251, London (1841).]

[30-*A*] Gauss, C. F. Intensitas vis magneticae terrestris ad mensuram absolutam revocata. Gauss, Werke, herausgegeben von der Kgl. Ges. Wiss., Göttingen, **5,** 79–118 (1877). Ostwalds Klassiker, Nr. 53. [This important work was completed in 1832 and published in 1833. A German translation was published in Pogg. Ann., **28,** (1833) and an Italian translation was issued by F. Frisiani, Milano (1837). In this paper Gauss proposed a system of units of length, mass, and time. He called these units absolute units and the unit of the magnetic field has been named the gauss.]

[31] Gauss, C. F., and W. Weber. Resultate aus den Beobachtungen des Magnetischen Vereins in den Jahren 1836–1841. 6 vols. Göttingen und Leipzig (1837–1843). Partly reprinted in Gauss, Werke. Some of the articles translated in Scientific Memoirs, edited by Richard Taylor, **2,** London (1841). [The volume for 1838 contains Allgemeine Theorie des Erdmagnetismus by C. F. Gauss.]

[32] Gilbert, W. De magnete. London (1600). [The title in full is as follows: Guilielmi Gilberti Colcestrensis, medici londinensis, De Magnete, magneticisque corporibus, et de magno magnete tellure; Physiologia nova, plurimis et argumentis et experimentis demonstrata. Londini, Excudebat Petrus Short anno MDC. Later editions were published at Stettin (Sedini) 1628, 1633, and at Frankfurt 1629, 1638. There is an English translation by P. Fleury Mottelay, published by John Wiley & Sons, Inc., New York, in 1893, and another, with notes by S. P. Thompson, issued by the Gilbert Club of London, in 1900. This outstanding contribution to magnetic science, which is distinguished by its strict adherence to the scientific method of investigation by experiment and by the originality of its contents, recounts the author's extensive experiments on magnets and magnetic bodies and on electrical attractions. In it is announced the author's epoch-making conception that the Earth is itself a great magnet and

that it is this that explains not only the north-south position assumed by the magnetic needle but the dipping or inclination of the needle as well.]

[33] Hansteen, Chr. Untersuchungen über den Magnetismus der Erde. Uebersetzt von P. T. Hanson. Christiania, xxx + 502 + 148 pp. (1819). [The first two sections deal with the history of magnetic observations up to about 1800. The theoretical considerations which follow have been long superseded. The chief value of the work today consists in the tables of results of determinations of declination and inclination made up to the time of publication, 1819. No estimation of the degree of accuracy of the values or indication of the sources from which they are taken, is given. A magnetic atlas of seven charts representing the change of the magnetic elements since 1600, accompanies the work.]

[34] Hazard, D. L. The Earth's magnetism. Washington, D. C., Dept. Comm., U. S. Coast Geod. Surv., Spec. Pub. No. 117, 52 pp. (1925). [This publication supersedes "Principal facts of the Earth's magnetism, etc." by L. A. Bauer, bringing the information up to date.]

[35] Hellmann, G. Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus, No. 4, Die ältesten Karten der Isogonen, Isoklinen, Isodynamen, 1701, 1721, 1768, 1804, 1825, 1826. [These reproductions include the isomagnetic charts of E. Halley (1701), W. Whiston (1721), J. C. Wilcke (1768), A. von Humboldt (1804), and C. Hansteen (1825, 1826).]

No. 9, H. Gellibrand, A discourse mathematical on the variation of the magneticall needle, London, 1635; No. 10, Rara magnetica, 1269–1599. [In No. 10 are reproduced ten very rare works which are of the highest importance to the student of the early history of terrestrial magnetism. Hellmann has also provided an introduction containing pertinent information regarding them. The ten papers are as follows: Petrus Peregrinus de Maricourt, De Magnete (1269); Francisco Falero, Del Nordestear de la Agujas (1535); Pedro Nunes, Estromento de Sombras (1537); João de Castro, Observações Magneticas (1538–1541); Georg Hartmann, Neigung der Magnetnadel (1544); Gerhard Mercator, De Ratione Magnetis circa Navigationem (1546); Martin Cortés, De la Piedra Yman (1551); Robert Norman, The Newe Attractiue (1581); William Borough, A Discours of the Variation (1581); Simon Stevin, De Havenvinding (1599).] Berlin, A. Asher und Co. (1895–1898).

[36] Lamont, J. Handbuch des Erdmagnetismus. Berlin, Veit und Comp., viii + 264 pp., 6 pls. (1849). [Contains theory of measurements.]

[37] Lamont, J. Handbuch des Magnetismus. Leipzig, Leopold Voss, viii + 468 pp. (1867).

[38] Lloyd, H. A treatise on magnetism, general and terrestrial. London, Longmans, Green & Company, xv + 239 pp. (1874).

[39] Lyons, T. A. A treatise on electromagnetic phenomena and on the compass and its deviations aboard ship. Mathematical, theoretical, and practical. New York, John Wiley & Sons, Inc., 2 vols. (1901, 1903). [The second volume contains a good discussion of the deviation of the compass.]

[40] Mascart, E. Traité de magnétisme terrestre. Paris, Gauthier-Villars, vi + 441 pp. (1900). [A general treatise on terrestrial magnetism primarily intended for the use of observers. The 14 chapters of which the book consists deal with the following subjects: Introductory remarks and definitions; potential; magnetization and magnetic induction; electromagnetism; magnets; instruments and methods for determining the direction and magnitude of the Earth's magnetic force; variations of the Earth's magnetism; magnetic perturbations; distribution of the Earth's magnetism; magnetic condition of the globe; various

phenomena (atmospheric electricity, auroras, earth-currents, industrial current-effects, earthquakes); and theory of compass-deviation.]

[41] Maurain, Ch. Physique du Globe. Paris, Armand Colin, vi + 204 pp. (1923). [Pp. 89–166 are devoted to the subject of terrestrial magnetism and pp. 167–201 to that of atmospheric electricity.]

[42] Maurain, Ch. Magnétisme et électricité terrestres. Fascicule I. Magnétisme terrestre. Paris, Hermann et Cie, 62 pp. (1935). [Actualités scientifiques et industrielles 287, Physique du Globe I.]

[43] Moos, N. A. F. Magnetic observations made at the Government Observatory, Bombay (Colaba magnetic data), for the period 1846 to 1905 and their discussion. Part I. Magnetic data and instruments. Part II. The phenomenon and its discussion. Bombay, Government Central Press, 2 vols. (1910).

[44] Nippoldt, A. Der Erdmagnetismus. Müller-Pouillets Lehrbuch der Physik, 11. Aufl., **5**, I, 398–484 (1928).

[45] Nippoldt, A. Erdmagnetismus und Polarlicht. Einführung in die Geophysik, **2**, 1–168. Berlin, Verlag von Julius Springer (1929).

[46] Nippoldt, A. Erdmagnetismus, Erdstrom, und Polarlicht. 4. verbesserte Auflage. Berlin u. Leipzig, Walter de Gruyter und Co., 128 pp. (1937). [Sammlung Göschen Nr. 175.]

[47] Schmidt, Ad. Erdmagnetismus. Encyklopädie der Mathematischen Wissenschaften, **6**, I, 266–396. Leipzig, B. G. Teubner (1917). [Best treatment from the mathematical standpoint.]

[48] Schmidt, Ad. Der Stand der erdmagnetischen Forschung. Zs. Geophysik, Braunschweig, **4**, 294–304 (1928). [Excellent review of status of research in terrestrial magnetism at time of writing.]

[49] Schuster, A. A critical examination of the possible causes of terrestrial magnetism. Proc. Phys. Soc., **24**, 121–137 (1912).

[50] Stewart, B. Hypothetical views regarding the connection between the state of the Sun and terrestrial magnetism. Encyclopaedia Britannica, 9th ed., **16**, 181–184 (1878). [The date appearing on the title-page of the volume is obviously in error; internal evidence in the article of which this section is a part, indicates that the date should be 1882 or 1883.]

[51] Swann, W. F. G. The Earth's magnetic field. Phil. Mag., London, **24**, 80–100 (1912).

[52] Walker, E. Terrestrial and cosmical magnetism. Cambridge, Deighton, Bell and Co., 336 + vi pp., 10 pls. (1866). [The Adams Prize Essay for 1865.]

(2) Solar magnetism

[53] Birkeland, Kr. Sur le magnétisme général du Soleil. C.-R. Acad. sci., **157**, 104–106, 275–277, 394–396 (1913). [See also *ibid.*, **150**, 246–248 (1910).]

[54] Cowling, T. G. On the radial limitation of the Sun's magnetic field. Mon. Not. R. Astr. Soc., **90**, 140–154 (1929). [See also later article (The magnetic field of sunspots), *ibid.*, **94**, 39–48 (1933) and comment by J. Larmor, *ibid.*, **94**, 469–471 (1934).]

[55] Cowling, T. G. Diamagnetism and drift currents in the solar atmosphere. Mon. Not. R. Astr. Soc., **92**, 407–413 (1932).

[56] Cowling, T. G. The electrical conductivity of an ionized gas in the presence of a magnetic field. Mon. Not. R. Astr. Soc., **93**, 90–98 (1933).

[57] Gunn, R. The Sun's radial magnetic gradient and atmosphere. Phys. Rev., **33**, 614–620 (1929).

[58] Hale, G. E. On the probable existence of a magnetic field in sunspots. Astroph. J., **28,** 315–343 (1908). [See also later articles, *ibid.*, **49,** 153–178 (1919); Proc. Nation. Acad. Sci., **8,** 168–170 (1922) and **10,** 53–55 (1924).]

[59] Hale, G. E. Preliminary results of an attempt to detect the general magnetic field of the Sun. Astroph. J., **38,** 27–98 (1913).

(*c*) *Expeditions* (*chronologically arranged*)

Under this heading are listed some of the more important expeditions during which magnetic, atmospheric-electric, or auroral observations were made. It has not seemed best to extend this part of the bibliography much beyond the beginning of the present century although some expeditions, for example, during the First International Polar Year 1882–83 were of importance. A description of this first great international enterprise, together with a list of the expeditions that participated therein, will be found in the first chapter of volume 1 of the two-volume work, "Die Deutschen Expeditionen und ihre Ergebnisse" by G. Neumayer, Berlin, Verlag von A. Asher und Co. (1890, 1891).

[60] Expédition Antarctique Belge. Résultats du voyage du S. Y. *Belgica* en 1897–1898–1899, sous le commandement de A. de Gerlache de Gomery. Rapports scientifiques, Météorologie: Aurores australes, par Henryk Arctowski. Anvers, J. E. Buschmann, 64 pp., 2 pls. (1901).

[61] Osservazioni scientifiche eseguite durante la spedizione polare di S. A. R. Luigi Amedeo di Savoia, Duca degli Abruzzi 1899–1900. Milano, Ulrico Hoepli, 723 pp. (1903). [Aurore boreali osservate nella Baia di Teplitz dal 13 settembre 1899 al 30 gennaio 1900 (pp. 195–207); osservazioni magnetische (pp. 435–501).]

[62] Expédition Norvégienne de 1899–1900 pour l'étude des aurores boréales. Résultats des recherches magnétiques, par Kr. Birkeland. Kristiania, Skr. Vid. selsk. I, No. 1, 80 pp., 12 pls. (1901).

[63] Schwedische Südpolar-Expedition 1901–1903. Wissenschaftliche Ergebnisse der Schwedischen Südpolar-Expedition 1901–1903, unter Leitung von Dr. Otto Nordenskjöld. **1,** Lief. 5. Erdmagnetische Ergebnisse von Kurt Molin. Stockholm, Lithographisches Institut des Generalstabs, 172 pp., 1 pl., 1 map (1920).

[64] Deutsche Südpolar-Expedition 1901–1903, im Auftrage des Reichsministeriums des Innern herausgegeben von Erich von Drygalski. Erdmagnetismus. **5** und **6,** mit Atlas. Berlin u. Leipzig, Walter de Gruyter und Co. (1907–1925).

[65] National Antarctic Expedition 1901–1904. Physical observations with discussions by various authors. v + 192 pp., 21 pls. (1908). [In this volume, antarctic observations of the aurora, 1902–03, and antarctic magnetic observations, 1902–04, are discussed, pp. 97–190.] Magnetic observations. vii + 274 pp., 43 pls. (1909). Published by the Royal Society of London.

[66] Norwegian Aurora Polaris Expedition 1902–1903. I. On the cause of magnetic storms and the origin of terrestrial magnetism, by Kr. Birkeland. First and second sections. Christiania, H. Aschenhoug & Co., 801 pp. (1908, 1913).

[67] Ziegler Polar Expedition 1903–1905. Anthony Fiala, Commander. Scientific results obtained under the direction of William J. Peters. Edited by J. A. Fleming. Washington, D. C., National Geographic Society (1907). [Magnetic observations and reductions, by W. J. Peters and J. A. Fleming, pp. 1–359. Notes and sketches of the aurora borealis, by A. Fiala, pp. 361–368, 19 colored pls.]

[68] Expédition Antarctique Française (1903–1905), commandée par le Dr. Jean Charcot. Hydrographie, physique du Globe, par A. Matha et J. J. Rey. Paris,

Gauthier-Villars (1911). [Électricité atmosphérique, par J. J. Rey, pp. 191–260; Magnétisme terrestre, par J. J. Rey, pp. 575–615.]

[69] Norwegian Arctic Expedition in the *Gjöa* 1903–1906. The scientific results of the Norwegian Arctic Expedition in the *Gjöa* 1903–1906 under the conduct of Roald Amundsen. Parts I, II, and III. Geofys. Pub., Oslo, **6** (1932); **7** (1933), and **8** (1930). [Parts II and III contain the results of observations in terrestrial magnetism.] Summary of chief results in Terr. Mag., **31,** 17–21 (1926); Geofys. Pub., Oslo, **3,** No. 8, 14 pp. (1925).

[70] Carnegie Institution of Washington, Department of Terrestrial Magnetism. Cruises of the *Galilee,* 1905–1908, and the *Carnegie,* 1909–1929, as well as land magnetic expeditions. [See under publications of observatories and institutions.]

[71] Deuxième Expédition Antarctique Française (1908–1910), commandée par le Dr. Jean Charcot. Sciences physiques; documents scientifiques. Électricité atmosphérique, par J. Rouch. Paris, Masson et Cie, 39 pp., 7 pls. (1913).

[72] British (Terra Nova) Antarctic Expedition 1910–1913. Terrestrial magnetism, by C. Chree. xii + 548 pp., 60 diagrams and curves. Observations of the aurora, by C. S. Wright, 46 pp., 6 figs. London, Harrison & Sons, Ltd. (1921).

[73] Australasian Antarctic Expedition, 1911–14. Scientific reports, Series B. **1,** Terrestrial magnetism. Part I. Field survey and reduction of magnetograph curves, by E. N. Webb. Part II. Analysis and discussion of magnetograph curves, by C. Chree. 285 pp., 18 pls. (1925). **2,** Terrestrial magnetism and related observations. Part I. Records of the aurora polaris, by Douglas Mawson. Part II. Magnetic disturbance and its relations to aurora, by C. Chree. 331 pp. (1925, 1929). Sydney, A. J. Kent, Government Printer.

[74] Hudson Bay Expedition, 1914. The Hudson Bay Expedition, 1914. By W. J. Peters. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **5,** 289–313 (1926). [Magnetic work along the coast of Labrador and shores of Hudson Bay and Hudson Strait.]

[75] *Maud* Expedition, 1918–1925. Magnetic, atmospheric-electric, and auroral results, *Maud* Expedition, 1918–1925. By H. U. Sverdrup. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **6,** 309–524 (1927).

[76] Die erdmagnetischen Beobachtungen von Dr. Filchner auf seiner Reise in China und Tibet in den Jahren 1926–1928. Bearbeitet von O. Venske. Berlin, Veröff. Met. Inst., No. 379 (Abh. **9,** No. 7), 28 pp. (1931).

[77] Die Arktisfahrt des Luftschiffes *Graf Zeppelin* im Juli 1931. Wissenschaftliche Ergebnisse. Petermanns Mitt., Ergänzungsheft Nr. 216 (1933). [Erdmagnetische Forschung, von K. Haussmann, pp. 78–80; Die magnetischen Arbeiten während der Arktisfahrt des Luftschiffes *Graf Zeppelin* 1931, von G. S. Ljungdahl, pp. 81–87, 3 pls.] [Also Terr. Mag., **36,** 349–355 (1931).]

[78] Année Polaire Internationale 1932–1933. Participation française. **1,** Introduction, magnétisme terrestre, aurores polaires, ozone atmosphérique, rayons cosmiques. Paris, Gauthier-Villars, 431 pp. (1936). **2,** Électricité atmosphérique, courants telluriques, actinométrie, radio-électricité, historique des missions, 259 pp. (1938).

[79] British Polar Year Expedition, Fort Rae, N. W. Canada 1932–33. Published under the direction of the British National Committee for the Polar Year. London, The Royal Society, 2 vols. (1937). [**1,** Discussion of results, meteorology, terrestrial magnetism and aurora, atmospheric electricity. **2,** Tables, meteorology, terrestrial magnetism, atmospheric electricity.]

[80] Oesterreichische Jan Mayen-Expedition 1932–1933. Erdmagnetische Beobachtungen der österreichischen Jan Mayen-Expedition im Polarjahre 1932–1933

von R. Kanitscheider und M. Toperczer. Wien, SitzBer. Akad. Wiss., II*a*, **144,** 517–559 (1935).

[81] Résultats des observations de l'Expédition Polonaise de l'Annéé Polaire 1932–33 à l'Ile des Ours, par J. Lugeon, C. Centkiewicz, et W. Lysakowski. Fasc. II, Magnétisme terrestre, 73 pp., 33 pls. Fasc. IV, Aurores polaires, 21 pp., 15 pls. Varsovie, Inst. National Mét. de Pologne (1936).

(*d*) *Popular addresses and essays of non-technical content*

[82] Ault, J. P. The purpose and progress of ocean surveys. Sci. Mon., **26,** 160–177 (1928).

[83] Bauer, L. A. The Earth's magnetism. The fourth "Halley Lecture" delivered in the schools of the University of Oxford on May 22, 1913. Bedrock, London, **2,** 273–294 (1913). [This lecture was reprinted, after revision by the author and with added illustrations, in the Annual Report of the Smithsonian Institution for 1913, pp. 195–212.]

[84] Bauer, L. A. Our Earth a great magnet. J. Frank. Inst., **181,** 601–628 (1916). [Annual lecture of the Carnegie Institution of Washington for 1915.]

[85] Fleming, J. A. The magnetic and electric survey of the Earth: its physical and cosmical bearings and development. J. Wash. Acad. Sci., **16,** 109–132 (1926). [A French translation of this lecture appeared in Rev. gén. sci., Paris, **37,** 454–467 (1926).]

[86] Fleming, J. A. The magnetism of the Earth. Sci. Mon., **33,** 74–77 (1931). [Radio talk presented over the Columbia Broadcasting System.]

[87] Fleming, J. A. Terrestrial magnetism and electricity. Annual progress-reports in the American Year Book beginning with 1932. New York, Amer. Year Book Corp. [Prior to 1932 these articles were contributed by D. L. Hazard.]

[88] Fleming, J. A. Time-changes of the Earth's magnetic field. Sci. Mon., **34,** 499–530 (1932). [Carnegie Inst. Wash., Sup. Pub. No. 5, 1–32 (1932).]

[89] Fleming, J. A. Earth physics and geographical progress. Part I—Contribution from special branches of Earth physics. Part II—Contribution through study of the Earth's magnetic field. Carnegie Inst. Wash., News Service Bull., **3,** 229–238 (1935). Proc. Second Gen. Assembly, Pan Amer. Inst. Geog. Hist., Washington, D. C., 1935, 338–345 (1937).

[90] Hazard, D. L. Terrestrial magnetism in the twentieth century. J. Wash. Acad. Sci., **15,** 111–125 (1925).

[91] Mayer, A. M. The Earth a great magnet. A lecture delivered before the Yale Scientific Club, February 14, 1872. New Haven, Conn., University Series, No. 9, 213–284 (1872).

[92] Nippoldt, A. Magnetische Kräfte über dem Meere. Meereskunde, Berlin, **16,** No. 9, 28 pp. (1929).

[93] Swann, W. F. G. The origin of the Earth's electric and magnetic phenomena. J. Frank. Inst., **201,** 143–176 (1926).

(*e*) *Instruments*

(1) Instruments and methods of measurement

[94] Angenheister, G. Magnetische Wage mit Fadenaufhängung. Zs. Geophysik, **2,** 43–44 (1926).

[95] Angenheister, G. Erdmagnetische Messungen. Handbuch der Physik, herausgegeben von H. Geiger und K. Scheel, **16,** 764–795 (1927).

[96] Angenheister, G. Instrumente und Messmethoden. Handbuch der Experimentalphysik, herausgegeben von W. Wien und F. Harms, **25, I,** 527–585 (1928).

[97] Barnett, S. J. A sine galvanometer for determining in absolute measure the horizontal intensity of the Earth's magnetic field. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **4,** 373–394 (1921).

[98] Bauer, L. A., and J. A. Fleming. The C.I.W. deflector in use on the *Carnegie* for determining the magnetic horizontal intensity and magnetic declination at sea. Terr. Mag., **18,** 57–62 (1913).

[99] Bauer, L. A., W. J. Peters, and J. A. Fleming. Compass-variometer. U. S. Patent No. 1,701,603 (Feb. 12, 1929). Also Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **5,** 341–357 (1926).

[100] Bidlingmaier, F. Der Doppelkompass, seine Theorie und Praxis (Sonderabdruck aus "Deutsche Südpolar-Expedition, 1901–1903," **5,** Erdmagnetismus, **1,** Heft 1.) Berlin, Georg Reimer, 104 pp., 14 figs. (1907). [See also Terr. Mag., **35,** 225–229 (1930).]

[101] Bock, R. Ein neuer magnetischer Normaltheodolit. Zs. Instrumentenk., **48,** 1–14 (1928).

[102] Cady, W. G. A direct recording declinograph. Terr. Mag., **11,** 145–152 (1906).

[103] Chree, C. The law of action between magnets and its bearing on the determination of the horizontal component of the Earth's magnetic force with unifilar magnetometers. Phil. Mag., **8,** 113–145 (1904).

[104] Chree, C. Observational methods in terrestrial magnetism. Dictionary of Applied Physics, edited by Sir Richard Glazebrook, **2,** 532–543 (1922). [See also for electromagnetic methods, F. E. Smith, *ibid.*, 528–532.]

[105] Dorsey, N. E. The theory of the earth-inductor as an inclinometer. Terr. Mag., **18,** 1–38 (1913).

[106] Duvall, C. R. Note on the computation of the moment of inertia of a magnet and its suspension. Terr. Mag., **34,** 303–308 (1929).

[107] Dye, D. W. A magnetometer for the measurement of the Earth's vertical magnetic intensity in C.G.S. measure. Proc. R. Soc., A, **117,** 434–458 (1928).

[108] Eblé, L. Manuel pratique de magnétisme terrestre. Paris, Les Presses Universitaires de France, 79 pp. (1929).

[109] Eschenhagen, M. Über erdmagnetische Intensitätsvariometer. Verh. D. physikal. Ges., **1,** 147–152 (1899); English translation, Terr. Mag. **5,** 59–62 (1900).

[110] Fanselau, G. Über Messungen mit dem Doppelkompass. Berlin, Veröff. met. Inst., No. 380, 186–193 (1931). [In appendix of Bericht über die Tätigkeit des Preuss. Met. Inst., 1930.]

[111] Fanselau, G. Der Doppelkompass als magnetisches Universalinstrument. Berlin, Veröff. met. Inst., No. 395, 132–136 (1933). [In appendix of Bericht über die Tätigkeit des Preuss. Met. Inst., 1932.]

[112] Field, M. B. The navigational magnetic compass considered as an instrument of precision. J. Inst. Elec. Eng., **57,** 349–386 (1919).

[113] Fisk, H. W. Dip-needle errors arising from minute pivot-defects. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **4,** 359–371 (1921).

[114] Fleming J. A. Two new types of magnetometers made by the Department of Terrestrial Magnetism of the Carnegie Institution of Washington. Terr. Mag., **16,** 1–12 (1911).

[115] Fleming, J. A. Description of the C.I.W. marine earth-inductor. Terr. Mag., **18,** 39–45 (1913). [Report on the above by C. W. Hewlett, *ibid.*, 46–48.]

[116] Fleming, J. A., and J. A. Widmer. Description of the C.I.W. combined magnetometer and earth-inductor. Terr. Mag., **18,** 105–110 (1913).

[117] Forbush, S. E. Some practical aspects of the theory of the unifilar horizontal-intensity variometer. Terr. Mag., **39,** 135–143 (1934).

[118] Fraser, H. A. D. The unifilar magnetometer of the magnetic survey of India. Terr. Mag., **6,** 65–69 (1901).

[119] Haalck, H. Ein neues erdmagnetisches Universalvariometer. Zs. Instrumentenk., **47,** 16–32 (1927).

[120] Hartnell, G. The vertical-intensity variometer. Terr. Mag., **24,** 49–64 (1919).

[121] Hartnell, G. Horizontal-intensity variometers. Washington, D. C., U. S. Coast Geod. Surv., Spec. Pub. No. 89, 62 pp., 1 pl. (1922).

[121-*A*] Hartnell, G. An intensity variometer corrected for temperature. Terr. Mag., **30,** 117–124 (1925).

[121-*B*] Hartnell, G. Distribution coefficients of magnets. Washington, D. C., U. S. Coast Geod. Surv., Spec. Pub., No. 157, iii + 30 pp. (1930).

[122] Hazard, D. L. Directions for magnetic measurements. Third edition. Washington, D. C., U. S. Coast Geod. Surv., Ser. No. 166, vi + 129 pp. (1930). [This publication is the standard manual for observers of the U. S. Coast and Geodetic Survey doing work in terrestrial magnetism but the subject-matter is so treated that any observer familiar with the use of instruments of precision may be able to determine satisfactorily the magnetic elements without other assistance than that afforded by these directions. The third edition (1930) differs from the previous ones (first, 1911; second, 1921) in that the directions for the operation of a magnetic observatory have been omitted since a separate manual on that subject is being prepared by H. E. McComb. Reprinted with corrections in 1938.]

[123] Haussmann, K. Der Magnettheodolit von Eschenhagen-Tesdorpf. Zs. Instrumentenk., **26,** 1–15 (1906).

[123-*A*] Heck, N. H., and W. E. Parker. Instructions for the compensation of the magnetic compass. Washington, D. C., U. S. Coast Geod. Surv., Spec. Pub., No. 96, iv + 49 pp., 21 figs. (1923).

[124] Heiland, C. A. Theory of Adolf Schmidt's horizontal field balance. Geophysical Prospecting 1929: Trans. Amer. Inst. Min. Metall. Eng., **81,** 261–314 (1929). [See also Zs. angew. Geophysik, **1,** 289, 329 (1924).]

[125] Heyl, P. R., and L. J. Briggs. The earth-inductor compass. Proc. Amer. Phil. Soc., **61,** 15–32 (1922).

[125-*A*] Howe, H. H. On the theory of the unifilar variometer. Terr. Mag., **42,** 29–42 (1937).

[126] Jenkins, W. A. On the determination of "H." Phil. Mag., **41,** 454–462 (1921). [Determination of the horizontal intensity by the author's method of opposed fields. See also previous article by the author in Phil. Mag., **26,** 752–774 (1913).]

[127] Johnson, E. A. Application of alternating-current methods of detection to earth-inductors for marine and land observations. Terr. Mag., **41,** 251–260 (1936).

[128] Johnson, E. A., and W. F. Steiner. An astatic magnetometer for measuring susceptibility. Rev. Sci. Instr., **8,** 236–238 (1937).

[129] Koenigsberger, J. Vertikalvariometer für Feldmessungen. Zs. Geophysik, **1,** 237–242 (1925).

[130] La Cour, D. A vertical-intensity magnetometer. Terr. Mag., **31,** 153–163 (1926); **32,** 16 (1927).

[131] La Cour, D. La balance de Godhavn. Balance magnétique à l'aimant monade dans l'air raréfié. Copenhagen, Met. Inst., Comm. Mag., No. 8, 28 pp. (1930).

[132] La Cour, D. Le quartz-magnétomètre QHM (quartz horizontal-force magnetometer). Copenhagen, Met. Inst., Comm. Mag., No. 15, 22 pp. (1936). [For report on use of this instrument see Fanselau, Zs. Geophysik, **12,** 192–197 (1936).]

[133] La Cour, D., and V. Laursen. Le variomètre de Copenhague. Copenhagen, Met. Inst., Comm. Mag., No. 11, 11 pp. (1930).

[134] Lloyd-Creak Dip Circle. The Lloyd-Creak dip circle for observations at sea. Terr. Mag., **6,** 119–121 (1901).

[135] Ludy, A. K. Variometer scale-value determinations with a large deflector. Terr. Mag., **34,** 63–66 (1929).

[136] Lyot, B. Magnétographe à inscription photographique visible sans développement. Paris, Bul. Soc. Astr. France, **42,** 402–405 (1928).

[137] McComb, H. E. Distribution-coefficients for vertical-intensity magnetic variometers. Terr. Mag., **34,** 59–61 (1929).

[138] McComb, H. E. Induction-coefficients for magnetometer-magnets. Terr. Mag., **34,** 241–247 (1929).

[139] McComb, H. E., and A. K. Ludy. Temperature-compensation and adjustment of magnetic variometers. Terr. Mag., **35,** 29–34 (1930).

[140] McNish, A. G. A new type of vertical-intensity induction-variometer. Terr. Mag., **41,** 161–172 (1936). [See also Rev. Sci. Instr., **7,** 336–338 (1936).]

[141] Meldau, H., and A. J. L. Moritz. Het kompas aan boord van ijzeren en stalen Schepen. Rotterdam, N. V. Observator, 120 pp., tables, pls. (1915).

[142] Muramoto, A. On the "Nippon Suirobu (Japanese Hydrographic Department) magnetometer." Hydrogr. Bull., Tokyo, **8,** 111–128, 5 pls. (1929); Jap. J. Astr. Geophys., **7,** 125–145 (1930).

[143] Nelson, J. H. An electromagnetic method of determining induction-coefficients of magnetometer-magnets. Terr. Mag., **43,** 159–165 (1938).

[144] Nettleton, H. R., and F. H. Llewellyn. A sensitive rotating-coil magnetometer. Proc. Phys. Soc., **42,** 501–520 (1930).

[145] Ogloblinsky, N. New universal theodolite for determination of the elements of terrestrial magnetism. St. Petersburg, v + 120 pp., pls., tables (1913). [Russian text. See also Terr. Mag., **18,** 185–192 (1913).]

[146] Ono, S. A new design of highly sensitive magnetic variometer. Geophys. Mag., Tokyo, **1,** 63–67 (1927).

[147] Peters, W. J. The Carnegie Institution marine collimating compass. Terr. Mag., **14,** 17–24 (1909). [See also Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **3,** 177–190 (1917).]

[148] Rose, N. V., and N. N. Trubiatchinsky. Kratkoe rukovodstvo dlia rabot po magnitnoi s'emke. (Brief manual for magnetic-survey work.) Leningrad, Central Geophysical Observatory, vii + 114 pp. (1928). [This manual, which is wholly in the Russian language, contains: General remarks; astronomical observations for magnetic survey; determination of the magnetic declination with Brunner-Chasselon theodolite; determination of horizontal intensity with Brunner-Chasselon theodolite; determination of horizontal intensity with electric magnetometer; determination of inclination with dip-circle; determination of inclination with earth-inductor; reduction of observations to epoch.]

[149] Ryd, V. H. On the scale value and base value of the H-variometer. Copenhagen, Met. Inst., Comm. Mag., No. 12, 11 pp. (1930).

[149-*A*] Schmidt, Ad. Die magnetischen Variationsinstrumente des Seddiner Observatoriums. Zs. Instrumentenk., **27,** 137–147 (1907).

[150] Schmidt, Ad. Über die gegenseitige Einwirkung zweier Magnete in beliebiger Lage. Terr. Mag., **17,** 181–232 (1912); **18,** 65–70 (1913). [A complete exposition of the mutual action of two magnets upon each other in all possible positions in space.]

[151] Schmidt, Ad. Ein Lokalvariometer für die Vertikalintensität. Berlin, Veröff. met. Inst., No. 284 (109)-(134) (1915); No. 290 (87)-(106) (1919). [In appendices of Berichte über die Tätigkeit des Preuss. Met. Inst., 1914 and 1915.]

[152] Schmidt, Ad. Über Schwingungen in einem unregelmässig veränderlichen Kraftfelde. Berlin, SitzBer. Ak. Wiss., 609–622 (1917).

[152-*A*] Schmidt, Ad. Eine photographische Registriereinrichtung mit weiter Zeitskala bei sparsamem Papierverbrauch. Berlin, Veröff. met. Inst., No. 335, 38–45 (1926). [In appendix of Bericht über die Tätigkeit des Preuss. Met. Inst., 1925.]

[153] Schück, A. Der Kompass. Hamburg (1911, 1915, and 1918). I. 46 Tafeln und Verzeichnis derselben. II. Sagen von der Erfindung des Kompasses. Magnet, Calamita, Bussole, Kompass. Die Vorgänger des Kompasses. Tafel 47–79 und Verzeichnis derselben. III. Nachtrag zu Der Kompass II. Armierte Magnetsteine (natürliche Magnete) mit verzierter Fassung. Tafel 80–88 und Verzeichnis derselben. [Very valuable contribution to the history of the compass illustrated by excellent plates.]

[154] Smith, F. E. On an electromagnetic method for the measurement of the horizontal intensity of the Earth's magnetic field. Phil. Trans. R. Soc., A, **223,** 175–200 (1922). [See also article by A. Schuster, Terr. Mag., **19,** 19–22 (1914).]

[155] Soule, F. M. Earth-inductor measurements aboard the *Carnegie,* Cruise VII. Terr. Mag., **35,** 103–109 (1930).

[156] Southampton, Ordnance Survey. A portable magnetometer of the null type. London, H. M. Stationery Office, 4 pp., 3 pls. (1930).

[157] Starling, S. G. The equilibrium of the magnetic compass in aeroplanes. Phil. Mag., **32,** 461–476 (1916).

[158] Steiner, W. F. A method for producing non-magnetic castings of copper, brass, and aluminum. Terr. Mag., **43,** 47–48 (1938).

[159] Tanakadate, A. Section 3 of "A magnetic survey of all Japan" by C. G. Knott and A. Tanakadate. Tokyo, J. Coll. Sci., **2,** Part 3, 175–193 (1888).

[160] Uljanin, W. Ein transportables elektrisches Magnetometer. Terr. Mag., **34,** 199–207 (1929).

[161] Uljanin, W. Ein Universal-Induktionsmagnetometer. Zs. Geophysik, **6,** 435–442 (1930).

[162] Vedy, L. G. On the determination of the horizontal component of the Earth's magnetic field by a coupled oscillation method. Cambridge, Proc. Phil. Soc., **28,** 109–114 (1932).

[163] Venske, O. Die innere Genauigkeit von Inklinationsmessungen mit dem Erdinduktor. Zs. Geophysik, **6,** 248–251 (1930).

[164] Walker, G. W. A portable variometer for magnetic surveying. Proc. R. Soc., A, **92,** 313–321 (1916).

[165] Watanabe, N. An electric magnetometer for traveling. Tokyo, Proc. Phys.-Math. Soc., **2,** 210–223, illus. (1920).

[166] Watson, W. A quartz-thread vertical force magnetograph. Phil. Mag., **7,** 393–399 (1904); Terr. Mag., **9,** 62–68 (1904).

[167] Wild, H. Theodolith für magnetische Landesaufnahmen. Zürich, Vierteljahrsch. Natf. Ges., **41,** 1–25 (1896).

[168] Yanovsky, B. M. Methods of obtaining permanent magnets in magnetometers for measuring the horizontal component of the Earth's field. J. Geophys., Leningrad, **6,** 1–16 (1929).

(2) Comparisons

[169] Bauer, L. A., and J. A. Fleming. Results of comparisons of magnetic standards, 1905–1914. Res. Dept. Terr. Mag., Carnegie Inst., Pub. 175, **2,** 211–278 (1915). For 1915–1921, *ibid.*, **4,** 395–475 (1921).

[170] Bauer, L. A., and J. A. Fleming. On magnetic standards and comparisons of the Department of Terrestrial Magnetism. Trans. Rome Meeting, 1922; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 3, 84–97 (1923).

[171] Chree, C. Comparison of magnetic standards at British observatories with a discussion of various instrumental questions involved. London, Met. Office, Geophys. Mem., No. 30, 269–288 (1926).

[172] Dye, D. W. Comparison measurements between Abinger and the N.P.L. standard horizontal-force magnetometers. Terr. Mag., **31,** 177–185 (1926).

[173] Fleming, J. A. Comparison of magnetic-observatory standards by the Carnegie Institution of Washington. Terr. Mag., **16,** 61–84, 137–162 (1911).

[174] Fleming, J. A. Intercomparisons of magnetic standards and control of standards. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 241–248 (1937).

[175] Forbush, S. E., and E. A. Johnson. Results of international comparisons of magnetic horizontal intensity with CIW sine-galvanometer 1. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 248–259 (1937).

[176] Janovsky, B. M. Comparison of magnetic standards at the Sloutzk and Rude Skov observatories by means of the quartz H-magnetometer. Leningrad, Glav. Geofiz. Obs., Inf. Sborn. Zem. Mag., No. 3, 37–42 (1937). [Russian text.]

[177] Rijckevorsel, E. van. An attempt to compare the instruments for absolute magnetic measurements at different observatories. Amsterdam, R. Met. Inst., 15 pp. (1890). [See also later publications on comparisons of instruments by the same author at different observatories published by the Royal Dutch Meteorological Institute.]

[178] Watson, W. A determination of the value of the Earth's magnetic field in international units and a comparison of the results with the values given by the Kew Observatory standard instruments. Phil. Trans. R. Soc., A, **198,** 431–462 (1902).

(*f*) *Permanent field*

(1) General

[179] Adams, L. H., and J. W. Green. The influence of hydrostatic pressure on the critical temperature of magnetization for iron and other materials. Phil. Mag., **12,** 361–380 (1931); Terr. Mag., **36,** 161–169 (1931).

[180] Angenheister, G. Die physikalische Natur des erdmagnetischen Feldes. Physik. Zs., Leipzig, **26,** 305–320 (1925).

[181] Bartels, J. The eccentric dipole approximating the Earth's magnetic field. Terr. Mag., **41,** 225–250 (1936).

[182] Bauer, L. A. The physical decomposition of the Earth's permanent magnetic field. Terr. Mag., **4,** 33–52 (1899); **6,** 13–24 (1901); **8,** 97–129 (1903); **9,** 113–133, 173–186 (1904).

[183] Bauer, L. A. The physical theory of the Earth's magnetic and electric phenomena. Terr. Mag., **15,** 107–128, 219–232 (1910); **16,** 33–52, 113–122, 233–236 (1911); **17,** 79–96, 115–140 (1912).

[184] Bauer, L. A. Chief results of a preliminary analysis of the Earth's magnetic field for 1922. Terr. Mag., **28,** 1–28 (1923). [Summaries of method of analysis and conclusions drawn are given in Science, **58,** 113–115 (1923) and Nature, **112,** 295–298 (1923).]

[185] Bezold, W. von. Zur Theorie des Erdmagnetismus. Berlin, SitzBer. Ak. Wiss., No. 18, 414–449 (1897). [This paper consists of two parts, the first dealing with the fundamental principles of Gauss's potential theory of the Earth's magnetism, especially with reference to the experimental verification of the assumption of a potential, and the second with the application of these considerations to the diurnal variation in connection with Schuster's investigations published in Phil. Trans. R. Soc., **130,** 467–518 (1889).]

[186] Chapman, S. Theories of terrestrial and solar magnetism. Dictionary of Applied Physics, edited by Sir Richard Glazebrook, **2,** 543–561 (1922).

[187] Chapman, S. Some problems of terrestrial magnetism. J. London Math. Soc., **2,** Pt. 2, 131–144 (1927). [The problems considered are grouped under three main headings: (1) The main magnetic field and its secular variation; (2) transient magnetic disturbance; and (3) the daily magnetic variations.]

[188] Chapman, S., and A. T. Price. The electric and magnetic state of the interior of the Earth, as inferred from terrestrial magnetic variations. Phil. Trans. R. Soc., A, **229,** 427–460 (1930).

[189] Dyson, F., and H. Furner. The Earth's magnetic potential. Mon. Not. R. Astr. Soc., Geophys. Sup., **1,** 76–88 (1923).

[190] Gunn, R. A theory of the permanent magnetic fields of the Sun and Earth. Phys. Rev., **34,** 335–343 (1929).

[191] Haalck, H. Über das Vorhandensein einer magnetischen Wirkung durch rotierende Massen und die Ursache des Erd- und Sonnenmagnetismus. Zs. Geophysik, **5,** 359–365 (1929). [Comments by T. Schlomka, *ibid.*, **8,** 84–87 (1932).]

[192] Haalck, H. Über eine neue physikalische Erklärung der Ursache des Erd- und Sonnenmagnetismus und des luftelektrischen Vertikalstromes. Zs. Geophysik, **12,** 112–123 (1936). [Comments by T. Schlomka, and replies by H. Haalck, *ibid.*, **13,** 126–131, 192–198 (1937).]

[193] Haalck, H. Über die physikalischen Ursachen des Magnetismus der Erde. Beitr. Geophysik, **52,** 243–269 (1938). [Eine zusammenfassende Darstellung nach der Theorie des Verfassers.]

[194] Malkin, N. Relation entre le potentiel et ses gradients sur une surface sphérique et son application à la théorie du magnétisme terrestre. Leningrad, C.-R. Acad. sci., No. 8, 739–755 (1930). [Russian text.]

[195] McNish, A. G. Geomagnetic coordinates for the entire Earth. Terr. Mag., **41,** 37–43 (1936).

[196] Nippoldt, A. Unsere heutige Kenntnis über die Verteilung des Erdmagnetismus. Zs. Geophysik, **5,** 351–358 (1929).

[197] Peters, W. J. Results from magnetic east-west paths around the Earth. Terr. Mag., **28,** 83–88 (1923).

[198] Schmidt, Ad. Mathematische Entwickelungen zur allgemeinen Theorie des Erdmagnetismus. Hamburg, Aus d. Arch. Seewarte, **12,** No. 3, 29 pp. (1889).

[199] Schmidt, Ad. Die Verteilung des erdmagnetischen Potentials in Bezug auf beliebige Durchmesser der Erde. Terr. Mag., **1,** 18–27 (1896).

[200] Schmidt, Ad. Der magnetische Zustand der Erde zur Epoche 1885.0 analytisch dargestellt. Hamburg, Aus d. Arch. Seewarte, **21,** No. 2, 75 pp. (1898).

[201] Schmidt, Ad. Zur Frage der Zerlegung des erdmagnetischen Feldes. Met. Zs., **28,** 49–53 (1911).

[202] Schmidt, Ad. Das erdmagnetische Aussenfeld. Zs. Geophysik, **1,** 3–13 (1925).

[203] Schmidt, Ad. Allgemeine Formeln zur Vereinfachung häufig wiederholter Potentialberechnungen durch Benutzung fester Stationsgruppen. Berlin, Abh. Met. Inst., **8,** No. 2, 5–21 (1925). [Archiv des Erdmagnetismus, Heft 5.]

[204] Schmidt, Ad. Der magnetische Mittelpunkt der Erde und seine Bedeutung. Beitr. Geophysik, **41,** 346–358 (1934).

[205] Schuster, A. On electric currents induced by rotating magnets, and their application to some phenomena of terrestrial magnetism. Terr. Mag., **1,** 1–17 (1896).

[206] Schuster, A. On some definite integrals and a new method of reducing a function of spherical coordinates to a series of spherical harmonics. Phil. Trans. R. Soc., A, **200,** 181–223 (1903). [See also Ad. Schmidt, Terr. Mag., **42,** 347–354 (1937), and Nachtrag dazu, *ibid.*, **43,** 135 (1938).]

[207] Schuster, A. A critical examination of the possible causes of terrestrial magnetism. Proc. Phys. Soc., **24,** 121–137 (1912).

[208] Smith, F. E. Theories of terrestrial magnetism. Addresses delivered at meeting of British Ass. Adv. Sci., Bristol, 1930, 24 pp. London, British Association (1930). [Excellent summary.]

[209] Steiner, L. On the magnetic field of the Earth. Terr. Mag., **16,** 221–232 (1911).

[210] Sutherland, W. The cause of the Earth's magnetism. Terr. Mag., **5,** 73–83 (1900); **8,** 49–52 (1903); **9,** 167–172 (1904); **13,** 155–158 (1908).

[211] Swann, W. F. G. The Earth's magnetic field. Phil. Mag., **24,** 80–100 (1912).

(2) Magnetic surveys, charts, and tables

[212] Bartels, J., and G. Fanselau. Geophysikalischer Mond-Almanach. Zs. Geophysik, **13,** 311–328 (1937). [Translation of first part explaining the tables, Terr. Mag., **43,** 155–158 (1938).]

[213] Bauer, L. A. Halley's earliest variation chart. (Reproduced in facsimile for the first time, from a photograph furnished by Thos. Ward, Esq., of the chart in his possession.) Terr. Mag., **1,** 28–31, 1 chart (1896).

[214] Bauer, L. A. The magnetic survey of the North Pacific Ocean; instruments, methods, and preliminary results. Terr. Mag., **11,** 65–92 (1906).

[215] Bauer, L. A., and W. J. Peters. Some discussions of ocean magnetic work. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **3,** 423–438 (1917). [Discussion particularly of magnetic charts and annual change.]

[216] Beattie, J. C. Report of a magnetic survey of South Africa. London, Royal Society, x + 235 pp., 8 charts (1909).

[217] Beattie, J. C. True isogonics, isoclinals, and lines of horizontal intensity for the northwestern parts of the Union of South Africa and for part of Great Namaqualand for the epoch July 1, 1908. Trans. R. Soc. S. Africa, **4,** 57–63, pls. (1914).

[218] Berlin, Deutsche Marineleitung. Linien gleicher Missweisung, magnetischer Horizontalintensität und Inklination. Berlin, Dietrich Reimer. [Issued for various epochs.]

[219] Bruckmann, W. Beobachtungen in den Schweizer Hochalpen über die Aenderungen der erdmagnetischen Kraft mit der Höhe. Berlin, Veröff. Met. Inst., No. 258 (Abh. **4,** No. 9), 26 pp., 4 figs., 1 chart (1913).

[220] Burgaud, M., and Fr. Lou. Carte magnétique de Chine. Shanghai, 74 pp., maps (1937). [Observatoire de Zi-ka-wei, Études sur le magnétisme terrestre. Étude 40, fasc. 10.]

[221] Carnegie Institution of Washington. Annual reports of the Director of the Department of Terrestrial Magnetism published in the Year Books of the Carnegie Institution of Washington, abstracts in Terr. Mag., also in later volumes

of the Trans. Amer. Geophys. Union. [Current reports on observatory and survey work carried out by the Carnegie Institution of Washington.]

[222] Chapman, S. On methods of representing the distribution of the magnetic force over the Earth's surface. London, Geog. J., **53,** 166–172 (1919).

[223] Churchman, J. An explanation of the magnetic atlas or variation chart, etc., projected on a plan entirely new, by which the magnetic variation on any part of the globe may be precisely determined for any time, past, present, or future, etc. Philadelphia, James and Johnson, xi + 46 + 5 pp. (1790).

[224] Churchman, J. The magnetic atlas or variation charts of the whole terraqueous globe; comprising a system of the variation and dip of the needle, by which, the observations being truly made, the longitude may be determined. London, printed for the author, by Darton and Harvey, xxix + 80 pp., 2 pls., 2 figs. (1794).

[225] Dodwell, G. F. Maps of South Australia showing approximate lines of equal declination, equal inclination, and equal horizontal intensity, each for the period 1912–1914. Adelaide, A. Vaughan (1915). [These three maps give provisional values based upon preliminary report of field-results obtained by the Department of Terrestrial Magnetism, published in the report of the Australasian Association for the Advancement of Science, **14** (1913), and from publications of the Department of Terrestrial Magnetism of the Carnegie Institution of Washington; they show that considerable local disturbance exists in parts of South Australia.]

[226] Farr, C. C. A magnetic survey of the Dominion of New Zealand and some of the outlying islands for the epoch 30th June, 1903. Wellington, Lands and Survey Dept., 64 pp., 18 maps (1916).

[227] Fisk, H. W. Isomagnetic charts of the arctic area. Trans. Amer. Geophys. Union, 12th annual meeting, 134–139 (1931).

[228] Fleming, J. A. Terrestrial magnetism. (Smithsonian Physical Tables, 8th revised edition). Smithsonian Inst. Misc. Collect., **88,** 575–591 (1933).

[229] Fleming, J. A. Continuation of the oceanic magnetic survey of the Carnegie Institution of Washington by the British Admiralty. Terr. Mag., **40,** 147–150 (1935).

[230] Gernet, A. Die endgültigen Ergebnisse der magnetischen Messungen in See der Jahre 1925 und 1926. Reval, Topo-Hüdrograafia Aastaraamat, 1928/29, 33–35 (1930). [Accompanied by three charts showing declination, horizontal and vertical intensities in and around the Baltic Sea, epoch 1926.5.]

[231] Hamburg, Deutsche Seewarte. Weltkarten der Deklination, Inklination, und Horizontalintensität. [Issued every five years.]

[232] Haussmann, K. Magnetische Vermessungen in Deutschland. Terr. Mag., **37,** 331–334 (1932). [Brief summary of magnetic-survey work in Germany.]

[233] Hazard, D. L. Alaska magnetic tables and magnetic charts for 1920. Washington, D. C., U. S. Coast Geod. Surv., Spec. Pub. No. 63, 31 pp., 3 maps (1920).

[234] Hellmann, G. Magnetische Kartographie in historisch-kritischer Darstellung. Berlin, Veröff. Met. Inst., No. 215 (Abh. **3,** No. 3), 61 pp. (1909). [Contains annotated bibliography of published magnetic charts 1700–1909.]

[235] Homéry, G. Déclinaison magnétique sur l'ensemble du Globe 1931. C.-R. Acad. sci., **196,** 797–800 (1933).

[236] Lewis, A. D. Magnetic declination in South Africa (1936) published in connection with the isogonic magnetic map of South Africa, south of latitude 18° south for the approximate epoch April, 1936, particularly of the Union of South Africa. Pretoria, Union of South Africa, Dept. Irrigation, 19 pp., 1 diagram and 1 map (1937).

[237] Ljungdahl, G. S. A magnetic survey of Sweden made by the Hydrographic Service in the years 1928–1930. Stockholm, Kungl. Sjökarteverket, 37 pp., 6 maps (1934).

[238] London, Admiralty. Curves of equal magnetic variation, horizontal force, and dip. Charts Nos. 2598, 3803, 3598. [Issued every five years, last charts for epoch 1937.]

[239] Lutzow-Holm, O. Carta magnética de la República Argentina, confeccionada para la época del 1° de enero de 1931. Buenos Aires, Min. Agric., Dir. Met. Geofis. Hidrol., Ser. A, No. 1, 15 pp., 3 figs., 1 map (1933). [Isogonic chart only.]

[240] Madinhac and Homery. Atlas magnétique. Publié sous la direction de Ch. Maurain avec la collaboration de L. Eblé par Mme de Madinhac et Mlle Homery. Paris, Bureau Central de Magnétisme Terrestre, 16 pp., 23 maps (1925).

[241] Neumayer, G. Atlas des Erdmagnetismus (Berghaus' Physikalischer Atlas, Abt. IV). Gotha, Justus Perthes, 20 pp., 5 maps (1891). [Contains world isomagnetic charts for declination, inclination, and horizontal intensity, epoch 1885.0; also charts showing change in magnetic declination in period from 1600–1858.]

[242] Nippoldt, A. Magnetische Karten von Südwestdeutschland für 1909 nach eigenen, im Anschluss an die preussische magnetische Landesaufnahme ausgeführten Messungen. Berlin, Veröff. met. Inst., No. 224, 62 pp., 4 charts, 2 pls. (1910).

[243] Rijckevorsel, E. van. A magnetic survey of the Netherlands for the epoch January 1, 1891. Rotterdam, Verh. Bat. Gen., 103 pp., charts, tables (1895).

[244] Rijckevorsel, E. van, and E. Engelenburg. Magnetic survey of the eastern part of Brazil. Amsterdam, Johannes Müller, 166 pp., 5 pls. (1890).

[245] Schedler, A., and M. Toperczer. Die Verteilung der erdmagnetischen Deklination in Oesterreich zur Epoche 1930.0. Wien, Jahrb. ZentrAnst. Met. Geodyn., Beiheft 2, zu Jahrg. 1929, 1–22, maps (1936). [See also Verteilung der erdmagnetischen Kraft in Oesterreich zur Epoche 1930.0, *ibid.*, 31–54, and Terr. Mag., **40,** 159–163 (1935).]

[246] Schmidt, Ad. Magnetische Karten von Norddeutschland für 1909 nach der von M. Eschenhagen und J. Edler in den Jahren 1898 bis 1903 ausgeführten magnetischen Landesaufnahme des Königl. Preuss. Meteorologischen Instituts. Berlin, Veröff. met. Inst., No. 217, 40 pp., 4 charts (1910).

[247] Schmidt, Ad. Die erdmagnetischen Verhältnisse in West- und Mitteleuropa zur Epoche 1921.0. Landolt-Börnstein, Physikalisch-Chemische Tabellen, 5. Aufl., **1,** 37–42 (1923). [Supplementary data in Ergänzungsbände.]

[248] Schmidt, Ad. Tafeln der normierten Kugelfunktionen und ihrer Ableitung nebst den Logarithmen dieser Zahlen sowie Formeln zur Entwicklung nach Kugelfunktionen. Gotha, Engelhard-Reyher Verlag., 52 pp. (1935). Reviewed in Terr. Mag., **41,** 264 (1936).

[249] Tanakadate, A. A magnetic survey of Japan reduced to the epoch 1895.0 and the sea level, carried out by order of the Earthquake Investigation Committee. Tokyo, J. Coll. Sci., **14,** xii + 180 (1904). [Appendix, consisting of 347 pp., 87 pls., and 11 maps, contains complete list of magnetic observations 1893–96.]

[250] Tokyo, Hydrographic Department. A magnetic survey of Japan for the epoch 1923.0 executed by the Hydrographic Department. Tokyo, Bull. Hydrogr., Dept., **5,** v + 172 pp., figs., maps (1926). [Previous surveys for epoch 1913.0, Bull. Hydrogr. Dept., **2** (1918); for epoch 1895.0, J. Coll. Sci., Imp. Univ. Tokyo, **14** (1904).]

[251] United States Coast and Geodetic Survey. United States magnetic tables and magnetic charts for 1925. Washington, D. C., U. S. Coast Geod. Surv., Ser. No. 453, 136 pp., 4 illus. (1929). [These tables supersede those previously published, the last preceding four being for the years 1902, 1905, 1910, and 1915, and contain in addition to introductory and explanatory matter: Results of observations at repeat-stations; tables for reducing results to January 1, 1925; and observed values of magnetic elements and corresponding values for January 1, 1925. Four charts, namely, lines of equal magnetic declination, inclination, horizontal intensity, and vertical intensity with lines of equal annual change in each case, accompany the volume. The tables for 1935 have just appeared (1938).]

[252] United States Hydrographic Office. World magnetic charts. The variation of the compass for the year 1935 (No. 2406); The magnetic inclination or dip for the year 1935 (No. 1700); The horizontal intensity of the Earth's magnetic force for the year 1935 (No. 1701). [These charts are constructed every five years and are designed primarily for the use of the mariner and aviator.]

[253] Weinberg, B. P. Catalogue of magnetic determinations in U.S.S.R. and in adjacent countries from 1556 to 1926. Leningrad, Central Geophysical Observatory, xxiii + 390 pp. (1929–1933). [This extensive compilation of magnetic values was issued in three parts in 1929, 1932, and 1933, respectively. With the third part, which was prepared in collaboration with I. M. Rogachev, were issued isogonic, isoclinic, and isodynamic (*H* and *Z*) charts of U.S.S.R. for the epoch 1930.]

(3) Observatories

Publications of observatories.—The various observatories in which magnetic elements are recorded usually publish their results in annual volumes although in some cases monthly bulletins are issued which can be bound together into a volume at the end of the year. These publications of observatories are issued by the private organizations or governmental bureaus under which the observatories are operated. During recent years a number of observatories which had been in operation for long periods have found it necessary to abandon their original sites because of disturbances caused by electric currents, for example, those from electric-car lines, and have either moved to new locations or have ceased to function altogether. To enumerate the large number of publications of observatories would exceed the limits of this bibliography, but a list of the observatories will be found in the compilation of the annual values of the magnetic elements at observatories which is regularly published by J. A. Fleming in Terr. Mag. In these lists are given the names and geographic coordinates of the observatories with the latest available annual values of declination, inclination, and intensity (horizontal and vertical). The last values published in Terr. Mag., **35**, 165–177 (1930) were brought up to date and printed in Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 323–330 (1937).

[254] Bauer, L. A., and J. A. Fleming. Magnetic observatories of the United States Coast and Geodetic Survey in operation July 1, 1902. Washington, D. C., U. S. Coast Geod. Surv., Rep. for 1902, App. No. 5, 301–331 (1903).

[255] Fleming, J. A. Construction of non-magnetic experiment building of the Department of Terrestrial Magnetism. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **4,** 351–358 (1921).

[256] Fleming, J. A., and W. F. Wallis. The construction and equipment of the Watheroo Magnetic Observatory in Western Australia. Terr. Mag., **25,** 1–6 (1920).

[257] Gernet, A. Das Vermessungschiff *Cecilie,* seine Instrumente und allgemeine Gesichtspunkte über die Ausführung der Vermessung. Reval, Topo-Hüdrograafia Aastaraamat, 75–81, 101–106 (1924).

[258] Hoge, E. Contribution à la connaissance de l'effet magnétique de l'électrification des chemins de fer. Copenhagen, Met. Inst., Comm. Mag., No. 18, 11 pp. (1937).

[259] Maurain, Ch. L'observatoire géophysique de Chambon-la-Forêt. Paris, Institut de Physique du Globe, 19 pp., 7 figs. (1937).

[260] Merlin, E., and O. Somville. Liste des observatoires magnétiques et des observatoires séismologiques. Bruxelles, Hayez, x + 192 pp. (1910). [This list contains over 200 observatories and gives information regarding their location, dependence, instruments, work, personnel, publications, etc. Very valuable at the time of its publication, it is now, of course, in many respects out of date, but it is the only publication on world magnetic observatories which has come to our notice. The Association of Terrestrial Magnetism and Electricity of the International Union of Geodesy and Geophysics is planning the early publication of a list of magnetic and electric observatories which will contain the latest available information.]

[261] Puig, I. El Observatorio del Ebro. Idea general sobre el mismo. Tortosa, Algueró y Baiges, viii + 188 pp., illus. (1927).

[262] Rose, N. Der Zustand des Netzes der magnetischen Observatorien der U.d.S.S.R. und weitere Perspektive seiner Entwickelung. Terr. Mag., **40,** 401–406 (1935).

[263] Schmidt, Ad. Das Variationshaus in Niemegk. Berlin, Veröff. met. Inst., No. 380, 59–64 (1931). [In appendix of Bericht über die Tätigkeit des Preuss. Met. Inst., 1930.]

[264] Wild, H. Über die Einrichtung erdmagnetischer Observatorien. St. Petersburg, Bull. Acad. Sci., **8,** 191–205 (1898). [See also Terr. Mag., **4,** 153–168, 169–198 (1899).]

(*g*) *Periodic variations* (*diurnal, lunar, annual, etc.*) *and magnetic activity*

[265] Angenheister, G. Sonnentätigkeit, Sonnenstrahlung, Lufttemperatur und erdmagnetische Aktivität im Verlauf einer Sonnenrotation. Terr. Mag., **25,** 17–26 (1920).

[266] Bartels, J. Die interdiurne Veränderlichkeit der Horizontalintensität als Mass für die erdmagnetische Aktivität. Met. Zs., **40,** 301–305 (1923).

[267] Bartels, J. Erdmagnetische Aktivität 1836–1923. Berlin, Abh. met. Inst., **8,** No. 2, 45–59 (1925).

[268] Bartels, J. Eine universelle Tagesperiode der erdmagnetischen Aktivität. Met. Zs., **42,** 147–152 (1925).

[269] Bartels, J. Use of magnetic data for investigating radiation from the Sun. Trans. Amer. Geophys. Union, 12th Annual Meeting, 126–131 (1931).

[270] Bartels, J. Statistical methods for research on diurnal variations. Terr. Mag., **37,** 291–302 (1932).

[271] Bartels, J. L'activité du magnétisme terrestre et ses relations avec les phénomènes solaires. C.-R. Cong. Internat. Paris 1932, **12,** 77–88 (1932).

[272] Bartels, J. Terrestrial-magnetic activity and its relation to solar phenomena. Terr. Mag., **37,** 1–52, 17 figs., 2 colored pls. (1932); **39,** 1–4, 201–202 (1934); **40,** 265–266 (1935); **41,** 374 (1936); **43,** 131–134 (1938).

[273] Bartels, J. Aufschlüsse über die Ionosphäre aus der Analyse sonnen- und mondentägiger erdmagnetischer Schwankungen. Zs. Geophysik, **12,** 368–376 (1936).

[274] Bauer, L. A. The local magnetic constant and its variations. Terr. Mag., **19,** 113–125 (1914). [For discussion of this subject by A. Nippoldt, see Terr. Mag., **37,** 279–286 (1932).]

[275] Bauer, L. A., and C. R. Duvall. Studies concerning the relation between the activity of the Sun and of the Earth's magnetism. Terr. Mag., **30,** 191–213 (1925); **31,** 37–47, 97–101 (1926).

[276] Bemmelen, W. van. Die lunare Variation des Erdmagnetismus. Met. Zs., **29,** 218–230 (1912); **30,** 589–594 (1913).

[277] Broun, J. A. On the relation of the variations of the horizontal intensity of the Earth's magnetism to the solar and lunar periods. Edinburgh, Trans. R. Soc., **16,** 99–109, 137–144 (1846).

[278] Chapman, S. On the diurnal variations of the Earth's magnetism produced by the Moon and Sun. Phil. Trans. R. Soc., A, **213,** 279–321 (1913). [See also Terr. Mag., **19,** 39–44 (1914).]

[279] Chapman, S. On the lunar diurnal variation of the Earth's magnetism at Pavlovsk and Pola (1897–1903). Phil. Trans. R. Soc., A, **214,** 295–317 (1914).

[280] Chapman, S. The lunar diurnal magnetic variation, and its change with lunar distance. Phil. Trans. R. Soc., A, **215,** 161–176 (1915).

[281] Chapman, S. The influence of solar activity on the lunar diurnal magnetic variation. Terr. Mag., **22,** 87–91 (1917).

[282] Chapman, S. The solar and lunar diurnal variations of terrestrial magnetism. Phil. Trans. R. Soc., A, **218,** 1–118 (1919).

[283] Chapman, S. Terrestrial magnetic variations and their connection with solar emissions which are absorbed in the Earth's outer atmosphere. Cambridge, Trans. Phil. Soc., **22,** 341–359 (1919).

[284] Chapman, S. The lunar diurnal magnetic variation at Greenwich and other observatories. Phil. Trans. R. Soc., A, **225,** 49–91 (1925).

[285] Chapman, S. On the diamagnetic field of the outer atmosphere. Terr. Mag., **34,** 1–16 (1929).

[286] Chapman, S. On the theory of the solar diurnal variation of the Earth's magnetism. Proc. R. Soc., A, **122,** 369–386 (1929).

[287] Chapman, S., and A. T. Price. On line-integrals of the diurnal magnetic variations. Proc. R. Soc., A, **119,** 182–196 (1928).

[288] Chapman, S., and J. M. Stagg. On the variability of the quiet-day diurnal magnetic variation. Proc. R. Soc., A, **123,** 27–53 (1929); **130,** 668–697 (1931).

[289] Chree, C. An inquiry into the nature of the relationship between sunspot frequency and terrestrial magnetism. Phil. Trans. R. Soc., A, **203,** 151–187 (1904).

[290] Chree, C. Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory. Phil. Trans. R. Soc., A, **212,** 75–116 (1912).

[291] Chree, C. The 27-day period in magnetic phenomena. Proc. R. Soc., A, **90,** 583–599 (1914).

[292] Chree, C. The difference between the magnetic diurnal variations on ordinary and quiet days at Kew Observatory. Proc. R. Soc., A, **91,** 370–381 (1915).

[293] Chree, C. Discussion of Kew magnetic data, especially the diurnal irregularities of horizontal force and vertical force, from ordinary days of the eleven years 1890 to 1900. Phil. Trans. R. Soc., A, **216,** 187–277 (1916).

[294] Chree, C. Magnetic "activity" and hourly ranges. Terr. Mag., **22,** 57–83 (1917).

[295] Chree, C. The 27-day period (interval) in terrestrial magnetism. Proc. R. Soc., A., **101,** 368–391 (1922).

[296] Chree, C. Absolute daily range of magnetic declination at Kew Observatory, 1858 to 1900. London, Met. Office, Geophys. Mem., No. 22, 19–47 (1923).

[297] Chree, C. The regular diurnal variation of magnetic declination at Kew Observatory from selected years of many and few sunspots, 1859–1894. London, Met. Office, Geophys. Mem., No. 43, 33 pp., 1 pl. (1928).

[298] Chree, C., and J. M. Stagg. Recurrence phenomena in terrestrial magnetism. Phil. Trans. R. Soc., A, **227**, 21–62 (1927).

[299] Cortie, A. L. The 27-day period (interval) in terrestrial magnetic disturbance. Proc. R. Soc., A, **106**, 19–32 (1924).

[300] Crichton Mitchell, A. Preliminary report on magnetic and electric characterization. Internat. Geod. Geophys. Union, Sect. Terr. Mag. Electr., Bull. No. 6, 3–9 (1926). [For further reports see Bull. No. 7, 57–64 (1929); No. 8, 205–206 (1931); No. 10, 185–186 (1937).]

[301] Crichton Mitchell, A., J. Egedal, and L. Elbé. Discussion on methods of numerical magnetic characterization of days. C.-R. Assemblée de Lisbonne 1933, Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 283–291 (1934).

[302] Davies, F. T. The diurnal variation in magnetic and auroral activity at three high-latitude stations. Terr. Mag., **40,** 173–182 (1935).

[303] Dijk, G. van. Activity of the Earth's magnetism and magnetic characterization of days. Utrecht, K. Ned. Met. Inst., Meded. Verh., No. 27, 28 pp., 23 tables (1922).

[304] Duvall, C. R. Magnetic activity—numerical magnetic character of days. Terr. Mag., **37**, 261–267 (1932). [See also *ibid.*, **36,** 311–314 (1931) and C.-R. Assemblée de Lisbonne 1933, Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 210–213 (1934); also J. Egedal, Terr. Mag., **40,** 205–207 (1935).]

[305] Egedal, J. The lunar-diurnal magnetic variation and its relation to the solar-diurnal variation. Terr. Mag., **31,** 193–199 (1926); **32,** 139–141 (1927).

[306] Egedal, J. Über eine Verbindung zwischen den mondentägigen und den sonnentägigen Variationen der magnetischen Deklination. Zs. Geophysik, **3,** 80–86 (1927).

[307] Ennis, C. C. Relationship between auroral and magnetic activities at Little America, First Byrd Antarctic Expedition, 1928–30. Terr. Mag., **41,** 45–55 (1936).

[308] Eschenhagen, M. Über schnelle, periodische Veränderungen des Erdmagnetismus von sehr kleiner Amplitude. Berlin, SitzBer. Ak. Wiss., 678–686 (1897). [Translation in Terr. Mag., **2,** 105–114 (1897).]

[309] Fisk, H. W. Some preliminary results of diurnal variation of magnetic inclination at field stations in South American countries. Terr. Mag., **31,** 165–176 (1926).

[310] Fisk, H. W. The lag between solar activity and magnetic activity. Terr. Mag., **34,** 147–150 (1929).

[311] Gunn, R. The diamagnetic layer of the Earth's atmosphere and its relation to the diurnal variation of terrestrial magnetism. Phys. Rev., **32,** 133–141 (1928).

[312] Gunn, R. The diamagnetic theory of undisturbed terrestrial-magnetic variations. Terr. Mag., **34,** 17–21 (1929).

[313] Johnston, H. F., and A. G. McNish. Variations du champ magnétique terrestre aux observatoires de Watheroo et de Huancayo et leurs relations avec les systèmes de courants à l'intérieur et au voisinage de la Terre. C.-R. Cong. Internat. Electr., Paris, **12,** 41–52 (1932).

[314] Lüdeling, G. Über die tägliche Variation des Erdmagnetismus an Polarstationen. Berlin, SitzBer. Ak. Wiss., 524–530 (1898).

[315] McNish, A. G. Secular change in the magnetic solar-diurnal variations at the Huancayo Magnetic Observatory. Terr. Mag., **40,** 151–158 (1935).

[315-*A*] McNish, A. G. Concerning non-cyclic change. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 265–270 (1937).

[316] McNish, A. G. Progress of research in magnetic diurnal variations at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 271–280 (1937).

[317] McNish, A. G., and A. K. Ludy. The American character-figure C_A as a measure of magnetic activity of the Earth. Terr. Mag., **42,** 173–177 (1937).

[318] Nippoldt, A. Die Verteilung der regelmässigen täglichen Variationen des Erdmagnetismus in Mitteleuropa. Zs. Geophysik, **5,** 80–83 (1929).

[319] Okada, T. On the vector-diagram representing the diurnal variations of horizontal intensity of the Earth's magnetic field. Geophys. Mag., Tokyo, **3,** 1–26. 12 pls. (1930).

[320] Price, A. T., and S. Chapman. On line-integrals of the diurnal magnetic variations. Proc. R. Soc., A, **119,** 182–196 (1928).

[321] Schmidt, Ad. Besitzt die tägliche erdmagnetische Schwankung in der Erdoberfläche ein Potential? Physik. Zs., **19,** 349–355 (1918).

[322] Schmidt, Ad. Über die Bestimmung der erdmagnetischen Aktivität. Terr. Mag., **25,** 123–138 (1920).

[323] Schmidt, Ad. Enthalten die Variationen des Erdmagnetismus einen Bestandteil, der in Beziehung zur Sternzeit steht? Berlin, Veröff. met. Inst., No. 355, 89–97 (1928).

[324] Schmidt, Ad. Der Einfluss des Mondes auf die erdmagnetischen Elemente in Potsdam und Seddin während der Jahre 1905–1924. Berlin, Veröff. met. Inst., Nr. 357 (Abh. **9,** Nr. 1) 25–80 (1928). [Archiv der Erdmagnetismus, Heft 7.]

[325] Schneider, O. Einflüsse der Sonne auf die lunare Variation des Erdmagnetismus. Berlin, Veröff. met. Inst. Univ., **1,** Heft 3, 43 pp. (1936).

[326] Schuster, A. The periodogram of magnetic declination as obtained from the records of the Greenwich Observatory during the years 1871–1895. Cambridge, Trans. Phil. Soc., **18,** 107–135 (1899).

[327] Schuster, A. The diurnal variation of terrestrial magnetism. London, Phil. Trans. R. Soc., A, **180,** 467–512 (1889), with appendix by H. Lamb on the currents induced in a spherical conductor by variation of an external magnetic potential, pp. 513–518; **208,** 163–204 (1908). [In the first of these fundamental memoirs, the author shows that the principal part of the diurnal variation of terrestrial magnetism has its origin outside the Earth's surface and draws the natural conclusion that it is caused by electric currents circulating in the upper regions of the atmosphere. In the second memoir he carries the investigation further and, treating the diurnal and semidiurnal variations separately, he finds that each of them is caused by an oscillation of the atmosphere which is of the same nature as that which causes the diurnal changes of barometric pressure.]

[328] Stagg, J. M. The absolute daily range of magnetic declination at Kew Observatory, Richmond, 1901 to 1910. London, Met. Office, Geophys. Mem., No. 29, 239–266 (1926).

[329] Stagg, J. M. On magnetic fluctuations and sunspot frequency. A discussion based primarily on the daily ranges of declination as recorded at Kew Observatory, Richmond, during the 67 years 1858–1924. London, Met. Office, Geophys. Mem., No. 36, 24 pp. (1927).

[330] Steiner, L. Über die tägliche Variation der erdmagnetischen Kraft. Met. Zs., **29,** 417–428 (1912).

[331] Vleuten, A. van. Over de dagelijksche variatie van het aardmagnetisme. Utrecht, K. Ned. Met. Inst., No. 102, 112 pp., 1 pl. (1917). [With this Dutch paper are bound English translations of two papers on the same subject, namely: On the question whether the internal magnetic field, to which the diurnal variation in terrestrial magnetism is partly ascribed, depends on induced currents, K. Ak. Wet. Amsterdam, **26,** 293–296 (1917); and Do the forces causing the diurnal variation of terrestrial magnetism possess a potential? *ibid.*, **26,** 297–299 (1917).]

[332] Walker, G. W. On a new analytical expression for the representation of the components of the diurnal variation of terrestrial magnetism. Proc. R. Soc., A, **88,** 191–194 (1913).

[333] Walker, G. W. The diurnal variation of terrestrial magnetism. Proc. R. Soc., A, **89,** 379–392 (1914).

[334] Wasserfall, K. F. On periodic variations in terrestrial magnetism. Studies based upon photographic records from the polar station Gjöahavn. Geofys. Pub., **5,** No. 3, 33 pp. (1927).

(*h*) *Secular variation*

[335] Bartels, J. Versuch einer analytischen Darstellung des Verlaufs der Säkular-Variation im Zeitraum 1902–1920. Berlin, Abh. Met. Inst., **8,** No. 2, 23–44 (1925). [Archiv des Erdmagnetismus, Heft 5.]

[336] Bauer, L. A. Beiträge zur Kenntniss des Wesens der Säcular-Variation des Erdmagnetismus. Diss. Univ. Berlin, 54 pp. (1895). [For Bauer's later papers pertaining to secular variation, see Terr. Mag., **37,** 220–224 (1932).]

[337] Bauer, L. A. Zur Theorie der Säkularvariation des Erdmagnetismus. Physik. Zs., **12,** 445–448 (1911).

[338] Bauer, L. A. Relation between the secular variation of the Earth's magnetism and solar activity. Terr. Mag., **23,** 1–22, 61–68 (1918).

[339] Bemmelen, W. van. De isogonen in de XVI^{de} en XVII^{de} eeuw. Proefschrift, Univ. Leiden, 48 pp., maps (1893).

[340] Bemmelen, W. van. Die Abweichung der Magnetnadel; Beobachtungen, Säcular-Variation, Wert- und Isogonensysteme bis zur Mitte des XVIII^{ten} Jahrhunderts. Batavia, Obsns. Mag. Met., Sup., **21,** 109, with 4 charts (1899).

[341] Bidlingmaier, Fr. Über das Wesen der Säkularen Variation des Erdmagnetismus, und Bestimmung ihres Ursprungsortes im Erdinnern. Physik. Zs., **11,** 1216–1222 (1910); **12,** 449–459, 926–927 (1911).

[342] Carlheim-Gyllensköld, V. Sur la forme analytique de l'attraction magnétique de la terre exprimée en fonction du temps. Stockholm, Astr. Iaktt., **5,** No. 5, 36 pp. (1896). [Review by Ad. Schmidt, Terr. Mag., **2,** 150–155 (1897), translated from Met. Zs., **14,** 39–42 (1897).]

[343] Fisk, H. W. Regional distribution of magnetic secular-variation over the Earth's surface. Trans. Amer. Geophys. Union, 11th Annual Meeting, 215–223 (1930).

[344] Fisk, H. W. Isopors and isoporic movements. C.-R. Assemblée de Stockholm, 1930; Union Géod. Géophys. Internat., Sec. Mag. Electr. Terr., Bull. No. 8, 280–292 (1931).

[345] Fisk, H. W. Magnetic secular-variation and solar activity. Internat. Res. Council, 3rd Rep. Comm. on Solar and Terrestrial Relationships, 52–59 (1931).

[346] Fisk, H. W. The unsymmetrical distribution of the magnetic secular variation. Terr. Mag., **37,** 235–240 (1932).

[347] Fisk, H. W., and J. A. Fleming. On the distribution of permanent repeat-stations. C.-R. Assemblée de Stockholm, 1930; Union Géod. Géophys. Internat., Sec. Mag. Electr. Terr., Bull. No. 8, 293–299 (1931).

[348] Fleming, J. A. Distribution of magnetic observatories and secular-variation stations. Terr. Mag., **37,** 245–251 (1932). [See also Ad. Schmidt, Beitr. Geophysik, **3,** 225–246 (1898); Zs. Geophysik, **4,** 299–304 (1928). Also tentative list of international repeat-stations for consideration by the special committee on magnetic secular-variation stations. C.-R. Assemblée de Lisbonne 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 120–134 (1934).]

[849] Fritsche, H. Die Elemente des Erdmagnetismus für die Epochen 1600, 1650, 1700, 1780, 1842, und 1885, und ihre saecularen Aenderungen, berechnet mit Hülfe der aus allen brauchbaren Beobachtungen, abgeleiteten Coefficienten der Gaussischen Allgemeinen Theorie des Erdmagnetismus. St. Petersburg, 112 pp. (1899).

[350] Green, J. W. Subcrustal convection-currents and magnetic secular variation. C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 231–234 (1934).

[351] Heck, N. H. Secular change in the magnetic elements in the United States (180 years of declination and 80 years of horizontal intensity). C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 263–276 (1934).

[352] Heck, N. H. Report of special committee on magnetic secular variation. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 189–208 (1937). [In this report are embodied special reports from France, Germany, Poland, China and Indo-China, and from the Carnegie Institution of Washington.]

[353] McNish, A. G. The apparent effect of magnetic activity upon the secular variation of the Earth's magnetic field. Trans. Amer. Geophys. Union, 14th Annual Meeting, 139–144 (1933); 15th Annual Meeting, 175–176 (1934).

[354] Nippoldt, A. Die Magnetisierung der Erde nach der geomagnetischen Konstanten der Observatorien. Terr. Mag., **37,** 279–286 (1932).

[355] Repeat-stations. Tentative list of international repeat-stations for consideration by the special committee on magnetic secular-variation stations. C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 120–134 (1934).

[356] Schmidt, Ad. Die erdmagnetische Säkularvariation. Physik. Zs., **22,** 152–159 (1921).

[357] Schmidt, Ad. Das Rätsel der erdmagnetischen Säkularvariation. Terr. Mag., **37,** 225–230 (1932).

[358] Schuster, A. On magnetic precession. London, Proc. Phys. Soc., **17,** 644–655 (1901). Phil. Mag., **1,** 314–324 (1901). [Attempt to explain secular variation on the basis of inertia of electric currents caused by the Earth's rotation. It was found that inertia would cause a "magnetic precession" but that it would be much slower than actually observed variations.]

(*i*) *Magnetic disturbances, pulsations, solar and cosmical relations*

[359] Angenheister, G. Über die Fortpflanzungs-Geschwindigkeit erdmagnetischer Störungen und Pulsationen. Terr. Mag., **25,** 26–32 (1920).

[360] Angenheister, G. Die erdmagnetischen Störungen nach den Beobachtungen des Samoa-Observatoriums. I. Teil. Göttingen, Nachr. Ges. Wiss., 1–42 (1924).

[361] Bartels, J. Random fluctuations, persistence, and quasi-persistence in geophysical and cosmical periodicities. Terr. Mag., **40,** 1–60 (1935).

[362] Bauer, L. A. Beginning and propagation of the magnetic disturbance of May 8, 1902, and of some other magnetic storms. Terr. Mag., **15,** 9–20 (1910).

[363] Bauer, L. A. Data for abruptly beginning magnetic disturbances, 1906–1909. Terr. Mag., **16,** 85–108, 163–204 (1911). [Contains reports from observatories in all parts of the world.]

[364] Bauer, L. A. Magnetic inspection trip and observations during total solar eclipse of April 28, 1911, at Manua, Samoa. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **2,** 201–209 (1915).

[365] Bauer, L. A., and W. J. Peters. Regarding abruptly beginning magnetic disturbances. Terr. Mag., **30,** 45–68 (1925).

[366] Bemmelen, W. van. Spasms in the terrestrial magnetic force at Batavia. Amsterdam, Proc. K. Akad. Wet., 202–211 (1899).

[367] Bemmelen, W. van. The magnetic "postturbation" and the current-vortices of Schmidt. Terr. Mag., **5,** 123–126 (1900).

[368] Bemmelen, W. van. Erdmagnetische Pulsationen. Batavia, Nat. Tijdsch., **62,** 71–88 (1902); Met. Zs., Hann-Band, 268–270 (1906).

[369] Bemmelen, W. van. The diurnal field of magnetic disturbance. Terr. Mag., **8,** 153–174 (1903).

[370] Bemmelen, W. van. On pulsations. Batavia, Obsns. Mag. Met., **29,** 1906, app., 10 pp. (1908).

[371] Birkeland, Kr. On the cause of magnetic storms and the origin of terrestrial magnetism. The Norwegian Aurora Polaris Expedition 1902–1903. **1,** sect. 1, viii + 315, 21 pls. (1908).

[372] Birkeland, Kr. Orages magnétiques et aurores polaires. Arch. Sci. Phys., Genève, **32,** 97–116, 3 pls. (1911).

[373] Birkeland, Kr. On a possible crucial test of the theories of auroral curtains and polar magnetic storms. Kristiania, Skr. Vid. selsk., I, No. 6, 6 pp. (1915).

[374] Birkeland, Kr. Are the solar corpuscular rays that penetrate into the Earth's atmosphere negative or positive rays? Kristiania, Skr. Vid. selsk., I, No. 1, 27 pp. (1916).

[375] Bosler, J. Sur les relations des orages magnétiques et des phénomènes solaires. Thèse, Univ. Paris, 96 pp. (1912).

[376] Chapman, S. The energy of magnetic storms. Mon. Not. R. Astr. Soc., **79,** 70–83 (1918). [See also Terr. Mag., **37,** 269–272 (1932).]

[377] Chapman, S. An outline of a theory of magnetic storms. Proc. R. Soc., A, **95,** 61–83 (1918).

[378] Chapman, S. On the times of sudden commencement of magnetic storms. London, Proc. Phys. Soc., **30,** 205–214 (1918).

[379] Chapman, S. Terrestrial magnetic variations and their connection with solar emissions which are absorbed in the Earth's outer atmosphere. Cambridge, Trans. Phil. Soc., **22,** 341–359 (1919).

[380] Chapman, S. Theories of magnetic storms. Observatory, **42,** 196–206 (1919).

[381] Chapman, S. The motion of a neutral ionized stream in the Earth's magnetic field. Cambridge, Proc. Phil. Soc., **21,** 577–594 (1923).

[382] Chapman, S. On certain average characteristics of world-wide magnetic disturbance. Proc. R. Soc., A, **115,** 242–267 (1927).

[383] Chapman, S. Solar streams of corpuscles: their geometry, absorption of light and penetration. London, Mon. Not. R. Astr. Soc., **89,** 456–470 (1929).

[384] Chapman, S. On solar ultra-violet radiation as the cause of aurorae and magnetic storms. Mon. Not. R. Astr. Soc., Geophys. Sup., **2,** 296–300 (1930).

[385] Chapman, S. Report on international collaboration to advance the study of the Moon's effect upon geophysical phenomena. C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 136–142 (1934).

[386] Chapman, S. The electric current-systems of magnetic storms. Terr. Mag., **40,** 349–370 (1935).

[387] Chapman, S., and V. C. A. Ferraro. The electrical state of solar streams of corpuscles. Mon. Not. R. Astr. Soc., **89,** 470–479 (1929).

[388] Chapman, S., and V. C. A. Ferraro. A new theory of magnetic storms. Terr. Mag., **36,** 77–97, 171–186 (1931); **37,** 147–156, 421–429 (1932); **38,** 79–96 (1933).

[389] Chapman, S., and T. T. Whitehead. The influence of electromagnetic induction within the Earth upon terrestrial magnetic storms. Proc. Internat. Math. Cong., Toronto, 1924, **2,** 313–337 (1924).

[390] Chree, C. Some phenomena of magnetic disturbances at Kew. Phil. Trans. R. Soc., A, **210,** 271–306 (1910).

[391] Chree, C. Some phenomena of sunspots and of terrestrial magnetism at Kew Observatory. Phil. Trans. R. Soc., A, **212,** 75–116 (1912); **213,** 245–277 (1913).

[392] Chree, C. The criterion of magnetic disturbance. Terr. Mag., **28,** 33–40 (1923).

[393] Chree, C. The times of "sudden commencements" (S. C.s) of magnetic storms; observation and theory. London, Proc. Phys. Soc., **38,** 35–46 (1925).

[394] Chree, C. Magnetic disturbance and the magnetic characterization of days. Beitr. Geophysik, **15,** 14–25 (1926).

[395] Chree, C. Magnetic disturbance and aurora as observed by the Australian Antarctic Expedition at Cape Denison in 1912 and 1913. London, Proc. Phys. Soc., **39,** 389–407 (1927).

[396] Cortie, A. L. Sunspots and terrestrial magnetic phenomena, 1898–1911. Mon. Not. R. Astr. Soc., **73,** 52–60, 148–155, 431–436 (1913). [The cause of the annual variation in magnetic disturbances; the greater magnetic storms; sunspot areas, magnetic storms, and the Sun's corona.]

[397] Ebert, H. Über Pulsationen von geringer Periodendauer in der erdmagnetischen Feldkraft. München, SitzBer. Ak. Wiss., 527–543 (1906). [English translation by P. H. Dike in Terr. Mag., **12,** 1–14 (1907).]

[398] Ellis, W. On the simultaneity of magnetic variations at different places on occasions of magnetic disturbance, and on the relation between magnetic and earth-current phenomena. Proc. R. Soc., **52,** 191–212 (1892). [Detailed investigation of the simultaneity of beginnings of magnetic storms. He discusses 17 selected cases of magnetic storms with abrupt beginnings as recorded at eight different observatories.]

[399] Faris, R. L. Times of abruptly beginning magnetic disturbances, as recorded at the Coast and Geodetic Survey magnetic observatories. Terr. Mag., **15,** 93–105 (1910).

[400] Gehlinsch, E. Forschungsmethoden über den Zusammenhang zwischen der Sonnenfleckentätigkeit und den erdmagnetischen Störungen. Zs. Geophysik, **6,** 271–284 (1930).

[401] Goldie, A. H. R. The electric field in terrestrial magnetic storms. Edinburgh, Trans. R. Soc., **57,** 143–177 (1931). [See review of this article in Terr. Mag., **37,** 474 (1932).]

[402] Greaves, W. M. H., and H. W. Newton. Magnetic storms and solar activity 1874 to 1927. Mon. Not. R. Astr. Soc., **89,** 84–92 (1928). [See also *ibid.*, **88,** 556–567 (1928).]

[403] Greaves, W. M. H., and H. W. Newton. On the recurrence of magnetic storms. Mon. Not. R. Astr. Soc., **89**, 641–646 (1929).

[404] Hale, G. E. The spectrohelioscope and its work. Part III. Solar eruptions and their apparent terrestrial effects. Astroph. J., **73**, 379–412 (1931).

[405] Harang, L. Observations of micropulsations in the magnetic records at Tromsö. Terr. Mag., **37**, 57–61 (1932).

[406] Hulburt, E. O. On the ultra-violet light theory of aurorae and magnetic storms. Phys. Rev., **34**, 344–351 (1929); **36**, 1560-1569 (1930). [See also *ibid.*, **31**, 1038–1039 (1928).]

[407] Hulburt, E. O. Terrestrial magnetic variations and aurorae. Rev. Modern Phys., **9**, 44–68 (1937).

[408] Johnston, H. F. Short-period magnetic pulsations at the Watheroo Magnetic Observatory. Trans. Edinburgh Meeting, 1936; Internat. Union Géod. Géophys., Ass. Terr. Mag. Electr., Bull. No. 10, 262–265 (1937).

[408-*A*] Lahiri, B. N., and A. T. Price. Electromagnetic induction in non-uniform conductors, and the determination of the conductivity of the Earth from terrestrial magnetic variations. Phil. Trans. R. Soc., A, **237**, 509–540 (1939).

[409] Lamb, H. On electrical motions in a spherical conductor. Phil. Trans. R. Soc., A, **174**, 519–549 (1883). [For extension of theory see *ibid.*, **180**, 513–518 (1889).]

[410] Lindemann, F. A. Note on the theory of magnetic storms. Phil. Mag., **38**, 669–684 (1919).

[411] Lodge, O. Magnetic storms and solar eruptions. Nature, **81**, 425–426 (1909).

[412] Lubiger, F. Über die vom Samoa-Observatorium registrierten erdmagnetischen Pulsationen. Zs. Geophysik, **11**, 116–126 (1935).

[413] McNish, A. G. Occurrence of sudden commencements at the Watheroo Magnetic Observatory. C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 234–238 (1934). [See also *ibid.*, 238–240 (1934).]

[414] McNish, A. G. A possible test for theories of magnetic diurnal-variations and of magnetic storms. Terr. Mag., **39**, 5-6 (1934).

[415] McNish, A. G. Progress-report on the investigation of magnetic bays. Trans. Amer. Geophys. Union, 17th Annual Meeting, I, 166–170 (1936). Trans. Edinburgh Meeting, 1936; Internat. Union Géod. Géophys., Ass. Terr. Mag. Electr., Bull. No. 10, 282–289 (1937).

[416] McNish, A. G. On the ultraviolet light theory of magnetic storms. Phys. Rev., **52**, 155–160 (1937).

[417] Maris, H. B. Seasonal variations in magnetic storms. Phys. Rev., **39**, 504–514 (1932).

[418] Maris, H. B., and E. O. Hulburt. A theory of auroras and magnetic storms. Phys. Rev., **33**, 412–431 (1929).

[419] Maris, H. B., and E. O. Hulburt. Comets and terrestrial magnetic storms. Phys. Rev., **33**, 1046–1060 (1929).

[420] Maris, H. B., and E. O. Hulburt. Wireless telegraphy and magnetic storms. Proc. Inst. Radio Eng., **17**, 494–500 (1929).

[421] Maunder, E. W. The "great" magnetic storms 1875 to 1903, and their association with sunspots as recorded at the Royal Observatory, Greenwich. Mon. Not. R. Astr. Soc., **64**, 205–224 (1904). [See also *ibid.*, **65**, 2–34 (1904); 538–559, 666–681 (1905). Astroph. J., **21**, 101–115 (1905). Discussed by A. L. Cortie, Mon. Not. R. Astr. Soc., **65**, 197–205 (1905).]

[422] Maunder, E. W. Magnetic disturbances (1882–1913) as recorded at the Royal Observatory, Greenwich, and their association with (sunspots and) solar rotation.

Mon. Not. R. Astr. Soc., **65,** 2-34, 538–559, 666–681 (1904–1905); **76,** 63–68 (1915). [The author has published several papers on this subject mostly in the Mon. Not. R. Astr. Soc. See also review by C. Chree of investigations of period 1882–1903 in Terr. Mag., **10,** 9–14 (1905).]

[423] Maurain, Ch. Sur les relations entre les perturbations magnétiques et l'activité solaire. Ann. Inst. Phys. Globe, Paris, **5,** 86–108 (1927). [See also C.-R. Acad. sci., **182,** 1550–1552 (1926).]

[424] Maurain, Ch. Perturbations magnétiques. Aurores polaires. C.-R. Cong. Internat. Electr., Paris, **12,** 59–76 (1932).

[425] Maurain, Ch. Sur l'intervalle de temps entre les phénomènes solaires et les perturbations magnétiques terrestres. Ann. Inst. Phys. Globe, Paris, **12,** 63–75 (1934).

[426] Menaw, F. On small local rapidly periodic magnetic fluctuations. Terr. Mag., **41,** 1–8 (1936).

[427] Pödder, A. Untersuchung der mikromagnetischen Oszillationen in Zui (Irkutsk) mit Hilfe der Induktionsspule. Beitr. Geophysik, **17,** 232–242 (1927).

[428] Price, A. T. Electromagnetic induction in a conducting sphere. Proc. London Math. Soc., **31,** 217–224 (1929); **33,** 233–245 (1930).

[429] Rodés, L. On the non-simultaneity of magnetic storms. Terr. Mag., **27,** 161–166 (1922).

[430] Rodés, L. Período diurno, anual, y secular en las perturbaciones súbitas del campo magnético terrestre. Terr. Mag., **37,** 273–277 (1932).

[431] Rolf, B. Giant micropulsations at Abisko. Terr. Mag., **36,** 9–14 (1931).

[432] Röstad, A. Beziehung der Nordlichterscheinungen zu den weltweiten magnetischen Störungen. Geofys. Pub. **10,** No. 10, 10 pp. (1935). [See also author's previous papers, Geofys. Pub., **5,** No. 5 (1928), **9,** No. 3 (1931); Beitr. Geophysik, **16,** 431–435 (1927).]

[433] Schmidt, Ad. Über die Ursache der magnetischen Stürme. Met. Zs., **16,** 385–397 (1899).

[434] Schmidt, Ad. Einige Gesichtspunkte für die Einrichtung erdmagnetischer Simultanbeobachtungen zur Erforschung der Ursachen der erdmagnetischen Störungen. Terr. Mag., **5,** 9–14 (1900).

[435] Schuster, A. Sunspots and magnetic storms. Mon. Not. R. Astr. Soc., **65,** 186–197 (1905).

[436] Schuster, A. The origin of magnetic storms. Proc. R. Soc., **85,** 44–50 (1911).

[437] Slaucitajs, L., and A. G. McNish. The field of magnetic storms as deduced from the mean difference of magnetic intensity on quiet and disturbed days. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 289–301 (1937).

[438] Stagg, J. M. Hourly character figures of magnetic disturbance at Kew Observatory, Richmond, 1913–23. London, Met. Office, Geophys. Mem., No. 32, 24 pp. (1926). [The diurnal variation of magnetic disturbance, sunspot relations to the variation of disturbance, larger scale variations of character-figures.]

[439] Stagg, J. M. The 27-day recurrence interval in magnetic disturbance. An examination made with the aid of hourly character figures. London, Met. Office, Geophys. Mem., No. 40, 8 pp. (1927).

[440] Stagg, J. M. The time interval between magnetic disturbance and associated sunspot changes. London, Met. Office, Geophys. Mem., No. 42, 16 pp. (1928).

[441] Stagg, J. M. The diurnal variation of magnetic disturbance in high latitudes. Proc. R. Soc., A, **149,** 298–311 (1935).

[442] Stagg, J. M. Numerical character-figures of magnetic disturbance in relation to geomagnetic latitude. Terr. Mag., **40**, 255–262 (1935).

[443] Steiner, L. On a special form of magnetic disturbances. Terr. Mag., **26**, 1–14 (1921).

[444] Störmer, C. On pulsations of terrestrial magnetism and their possible explanation by periodic orbits of corpuscular rays. Terr. Mag., **36**, 133–138 (1931).

[445] Torreson, O. W., F. T. Davies, W. E. Scott, and H. E. Stanton. A solar eruption on November 6, 1936, and disturbances in Earth's magnetism, earth-currents, and the ionospheric regions. Terr. Mag., **41**, 409–410 (1936).

[446] Vacquier, V. Short-time magnetic fluctuations of local character. Terr. Mag., **42**, 17–28 (1937).

[447] Wallis, W. F. The geographical distribution of magnetic disturbance. Terr. Mag., **36**, 15–22 (1931). [See also *ibid.*, **35**, 93–101 (1930).]

[448] Wiechert, E. Untersuchungen an Baystörungen unter besonderer Berücksichtigung der Störmerschen Theorie. Königsberg/Pr., Mitt. Geophys. Warte Gr. Raum, No. 22, 26 pp. (1934).

(*j*) *Magnetic anomalies*

(1) Local magnetic anomalies

A large number of papers have been written describing various local anomalies in different parts of the Earth. Below are given a few of the more detailed and general papers of this type.

[449] Baseler, O. Die Vermessung der erdmagnetischen Anomalie bei Pr.-Eylau in Ostpreussen und ein Versuch ihrer Deutung. Beitr. Geophysik, Ergänzungshefte, **2**, 69–121 (1931).

[450] Brunhes, B. Sur la direction de l'aimantation permanente dans une argile métamorphique de Pontfarein (Cantal). C.-R. Acad. sci., **141**, 567–568 (1905).

[451] Carlheim-Gyllensköld, V. A brief account of a magnetic survey of the iron-ore field of Kiirunavaara made in the years 1900 to 1910 under the supervision of V. Carlheim-Gyllensköld. Stockholm, P. A. Norstedt & Söner, 34 pp., 2 maps (1910). [Investigation of the magnetic ore-deposits by means of magnetic measurements; analytical expression of the forces due to magnetization of an ellipsoid; application of a new method to an example.]

[452] Creak, E. W. On local magnetic disturbance in islands situated far from a continent. Proc. R. Soc., **40**, 83–93 (1886).

[453] Errulat, F. Über den Stand der Erforschung der erdmagnetischen Störungen in Ostpreussen. Königsberg i. Pr., Schr. Phys.-ökon. Ges., **64**, 30–41 (1925).

[454] Gamburzeff, G. A., and M. Polikarpoff. Beitrag zur Frage nach der Ursache der Kursker magnetischen und gravimetrischen Anomalie. Beitr. Geophysik, **19**, 219–230 (1928).

[455] Gelletich, H. Über magnetitführende eruptive Gänge und Gangsysteme im mittleren Teil des südlichen Transvaals. Beitr. angew. Geophysik, **6**, 337–406 (1937).

[456] Haalck, H. Über die Ursache der erdmagnetischen Störung im Gebiet der Freien Stadt Danzig. Zs. Geophysik, **6**, 129–140 (1930).

[457] Heiland, C. A. Possible causes of abnormal polarizations of magnetic formations. Zs. Geophysik, **6**, 228–235 (1930).

[458] Jenny, W. P. Problems in the geologic interpretation of the Earth's major magnetic anomalies. Terr. Mag., **38**, 97–105 (1933).

[459] Koenigsberger, J. Messung lokaler erdmagnetischer Anomalien zur Bestimmung des Gesteinsmagnetismus im Feld und zur Vergleichung mit dem Handstück; Beschreibung eines Variometers für den erdmagnetischen Vektor. Beitr. Geophysik, **23**, 248–268 (1929).

[460] Lasareff, P. The anomalies of terrestrial magnetism and gravity in the Kursk Government, Russia. Terr. Mag., **28**, 123–124 (1923); **30**, 11–14 (1925). [See also Rev. gén. sci., **35**, 582–584 (1924). A considerable number of articles were published by Lasareff on the above-named anomaly in J. Physique, Paris, and C.-R. Acad. sci., during 1923 and 1924.]

[461] Lasareff, P. Die Anomalie des Erdmagnetismus und der Gravitation im Kursker Gouvernement. Beitr. Geophysik, **15**, 71–89, 91–102 (1926).

[462] Lasareff, P. L'anomalie magnétique de Koursk. Atlas des cartes des éléments magnétiques mesurés sous la direction de P. Lazareff. Moscow, Promizdat, v + 27 pp. with charts (1927).

[463] Logachev, A. A. Experimental magnetic survey from an airplane. Razvedka Nedr, No. 17, 40–41 (1936). [Russian text. Description of apparatus, results over known anomaly at altitude of about 300 meters. Author concludes that measurement from an airplane of magnetic anomalies of intensity over 1,000 gammas is possible with his apparatus.]

[464] London, Admiralty. List of spots suitable for magnetic observations and list of places where abnormal variations have been reported. London, Admiralty, Hydrogr. Dept., Compass Branch (H. D. No. 211), 33 pp. (1908).

[465] Maurain, Ch. Étude détaillée d'une région de forte anomalie magnétique en Bretagne. Paris, C.-R. Acad. sci., **178**, 508–510 (1924).

[466] Nippoldt, A. Karten der Verteilung des Erdmagnetismus und seiner örtlichen Störungen in Europa. Berlin, Abh. Met. Inst., **8**, No. 11, 42 pp. with charts (1927). [Archiv des Erdmagnetismus, Heft 6.]

[467] Reich, H. Zur Frage der regionalen, magnetischen Anomalien Deutschlands, insbesondere derjenigen Norddeutschlands. Zs. Geophysik, **4**, 84–102 (1928).

[468] Schuh, F. Die geologische Bedeutung der Schaffung einer Isanomalenkarte der magnetischen Vertikalintensität von Deutschland. Zs. Geophysik, **6**, 235–248 (1930).

[469] Turcev. A. Contribution to the question of the magnetic anomaly in Karadagh, Crimea. Leningrad, Bull. Acad. sci., Nos. 9–11, 805–824 (1927). [Russian text with English summary.]

[470] Visser, S. W. On anomalies of terrestrial magnetism. Proc. 5th Pacific Sci. Cong., Canada, 1933, **3**, 1883–1891, 1893–1907 (1934). Amsterdam, Proc. Akad. Wet., **37**, 76–81, 118–122 (1934).

(2) Magnetism of rocks, etc.

[471] Chevallier, R. L'aimantation des laves de l'Etna et l'orientation du champ terrestre en Sicile du XII^{e} au XVII^{e} siècle. Ann. Phys., Paris, Ser. 10, **4**, 5–162 (1925).

[472] Grenet, G. Sur les propriétés magnétiques des roches. Ann. Phys., Paris, Ser. 10, **13**, 263–348 (1930).

[473] Koenigsberger, J. Method for measuring the susceptibility of rocks. Terr. Mag., **34**, 209–214 (1929).

[474] Koenigsberger, J. Grossenverhältnis von remanentem zu induziertem Magnetismus in Gesteinen; Grosse und Richtung des remanenten Magnetismus. Zs. Geophysik, **6**, 190–207 (1930).

[475] Koenigsberger, J. Zu Folgheraiters Bestimmungen des magnetischen Erdfeldes aus der Magnetisierung gebrannter Tongegenstände. Beitr. Geophysik, **35,** 51–54 (1932). [Foot-notes contain several references to papers on the subject.]

[476] Koenigsberger, J. G. Natural residual magnetism of eruptive rocks. Terr. Mag., **43,** 119–130, 299–320 (1938).

[477] Loewinson-Lessing. F., and A. Turcev. Recherches expérimentales sur l'aimantation permanente de roches soumises au chauffage. Leningrad, C.-R. Acad. sci., 161–165, 341–346, 875–886 (1927); Izv. Geol. Kom., **44,** 595–621 (1925).

[478] Mercanton, P. L. État magnétique de terres cuites préhistoriques. Lausanne, Bull. Soc. Sci. Nat., **52,** No. 194, 9–15 (1918); Paris, C.-R. Acad. sci., **166,** 681–682, 949 (1918).

[479] Reich, H. Eigenschaften der Gesteine. Handbuch der Geophysik, herausgegeben von B. Gutenberg, **6,** Lief. 1, 1–83 (1931).

[480] Rücker, A. W. On the relation between the magnetic permeability of rocks and regional magnetic disturbances. Proc. R. Soc., **48,** 505–535 (1890).

[481] Thellier, E. Détermination de la direction de l'aimentation permanente des roches. C.-R. Acad. sci., **203,** 743–744 (1936).

[482] Turcev, A. Investigation of the magnetic properties of rocks. Leningrad, Bull. Acad. sci., 89–112 (1928).

(*B*) TERRESTRIAL ELECTRICITY

(*a*) *General*

(1) Handbook articles, theoretical and descriptive papers

[483] Angenheister, G. Atmosphärische Elektrizität. Handbuch der Physik, herausgegeben von H. Geiger und K. Scheel, **14,** 405–441 (1927).

[484] Benndorf, H. Über die nächsten Aufgaben luftelektrischer Forschung. Zs. Geophysik, **1,** 147–152 (1925).

[485] Benndorf, H. Über das Grundproblem luftelektrischer Forschung. Physik. Zs., **26,** 81–91 (1925).

[486] Benndorf, H. Grundzüge einer Theorie des elektrischen Feldes der Erde. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **134,** 281–315 (1925); **136,** 175–194 (1927).

[487] Benndorf, H. Die elektrischen Vorgänge in der Atmosphäre. Lehrbuch der Geophysik, herausgegeben von B. Gutenberg. Berlin, Verlag von Gebrüder Borntraeger, Abschnitt 15, 730–796 (1929).

[488] Benndorf, H. Atmosphärische Elektrizität. Handbuch der Experimentalphysik, herausgegeben von W. Wien und F. Harms, **25, I,** 257–381 (1928).

[489] Benndorf, H., and V. F. Hess. Luftelektrizität. Müller-Pouillets Lehrbuch der Physik, 11. Aufl., **5,** I, 519–661 (1928).

[490] Chauveau, B. Électricité atmosphérique. Paris, Librairie Octave Doin. [This treatise appeared in three parts: I. Introduction historique. x + 90 pp. (1922). II. Le champ électrique de l'atmosphère. x + 264 pp. (1925). III. Généralités sur les ions, l'ionisation, et la radioactivité. xi + 240 pp. (1924).]

[491] Dobson, G. A comparison of the electrical conditions of the atmosphere at Kew and Eskdalemuir, with notes on observations of atmospheric electricity made in other countries. London, Met. Office, Geophys. Mem., No. 7, 153–169 (1914). [The following conditions are discussed: the electric potential-gradient in the air near the ground, the number of ions of both signs and their respective mobilities, the electric conductivity of the air, and the vertical electric current passing from the air to the Earth.]

[492] Gerdien, H. Der Elektrizitätshaushalt der Erde und der unteren Schichten der Atmosphäre. Physik. Zs., **6,** 647–666 (1905).

[493] Gish, O. H. Atmospheric electricity. (Smithsonian Physical Tables, 8th rev. ed.) Smithsonian Inst. Misc. Collect., **88,** 596–598 (1933).

[494] Gish, O. H. Report of the committee for the study of electrical characterization of days. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 208–213 (1937).

[495] Gockel, A. Die Luftelektrizität. Methoden und Resultate der neueren Forschung. Leipzig, S. Hirzel, vi + 206 pp. (1908).

[496] Humphreys, W. J. Physics of the air. New York, McGraw-Hill Book Company, Inc., 2d ed., xii + 654 pp. (1929).

[497] Kähler, K. Luftelektrizität. Berlin u. Leipzig, Vereinigung Wissenschaftlicher Verleger, Walter de Gruyter und Co., 1. Aufl., 151 pp. (1913); 2. Aufl., 134 pp. (1921). [Sammlung Göschen Nr. 649.]

[498] Kähler, K. Einführung in die atmosphärische Elektrizität. Berlin, Gebrüder Borntraeger, vi + 244 pp. (1929). [Gives details of instruments and technique of measurements. Theoretical considerations introduced only so far as necessary for an understanding of methods of measurement.]

[499] Le Cadet, G. Étude du champ électrique de l'atmosphère. Ann. Univ. Lyon, fasc. 35, 198 pp., 3 figs., 10 pls. (1898). [Review by A. McAdie, Terr. Mag., **4,** 145–148 (1899).]

[500] Le Cadet, G. Étude de l'électricité atmosphérique par beau temps au sommet du Mont-Blanc. Lyon, Mém. Acad. sci. bel.-let., 31 pp., 2 pls. (1904). [See also, Paris, C.-R. Acad. sci., **136,** 886–888 (1903).]

[501] Mache, H., and E. v. Schweidler. Die atmosphärische Elektrizität. Methoden und Ergebnisse der modernen luftelektrischen Forschung. Braunschweig, Vieweg, xi + 247 pp. (1909).

[502] Mathias, E., and collaborators. Traité d'électricité atmosphérique et tellurique. Paris, Les Presses Universitaires de France, xx + 580 pp. (1924). [Valuable work of reference.]

[503] Mendenhall, T. C. Report of studies of atmospheric electricity. Mem. Nation. Acad. Sci., **5,** 113–318 (1889).

[504] Negro, C. Elettricità atmosferica. Milano, Ulrico Hoepli, xvi + 299 pp. (1926).

[505] Ramsauer, C. Über den unmittelbaren Nachweis der elektrischen Erdladung. Ann. Physik, **75,** 449–458 (1924). [Remarks by T. Schlomka, *ibid.*, **78,** 204–208 (1925).]

[506] Riecke, E. Beiträge zu der Lehre von der Luftelektrizität. Ann. Physik, **12,** 52–84 (1903).

[507] Schlomka, T. Zur Theorie des elektrischen Feldes der Erde. Beitr. Geophysik, **24,** 241–272 (1929).

[508] Schonland, B. F. J. Atmospheric electricity. London, Methuen & Co., Ltd., vii + 100 pp. (1932).

[509] Schweidler, E. v. Atmosphärische Elektrizität. Encyklopädie der Mathematischen Wissenschaften, **6,** I, B, 235–265. Leipzig, B. G. Teubner (1915). [Historische Übersicht; Problemstellung; die Quellen der Ionisierung; der Ionisationszustand der Atmosphäre; das elektrische Feld und die Raumladung der Atmosphäre; die elektrischen Ströme in der Atmosphäre; das gestörte Feld der Troposphäre; elektrische Erscheinungen in der Stratosphäre (Polarlicht).]

[510] Schweidler, E. Über Versuche zum Nachweis einer negativen Korpuskularstrahlung kosmischen Ursprungs. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **127,** 515–533 (1918).

[511] Schweidler, E. Luftelektrizität. Einführung in die Geophysik, **2**, 291–375. Berlin, Verlag von Julius Springer (1929).

[512] Schweidler, E. Die Aufrechterhaltung der elektrischen Ladung der Erde. Hamburg, Henri Grand, iii + 68 pp. (1932).

[513] Schweidler, E. v., and K. W. F. Kohlrausch. Atmosphärische Elektrizität. Handbuch der Elektrizität und des Magnetismus, herausgegeben von L. Graetz, **3,** II, 181–276 (1915).

[514] Scrase, F. J. Observations of atmospheric electricity at Kew Observatory. A survey of results obtained from 1843 to 1931. London, Met. Office, Geophys. Mem., No. 60, 27 pp. (1934). [Historical introduction, methods of observation, potential-gradient reduction factors, the variation of potential-gradient in fine weather, comparisons of conductivity as measured by the Wilson apparatus at ground-level and on a tripod, conversion of the tripod observations of conductivity and current to values pertaining to ground-level, the variation of air-earth current and conductivity.]

[515] Seeliger, R. Die Aufrechterhaltung der negativen Erdladung, das Grundproblem der luftelektrischen Forschung. Ann. Physik, Leipzig, **62,** 464–481 (1920). [See also remarks on the above paper by E. Schweidler, *ibid.*, **63,** 726–738 (1920).]

[516] Simpson, G. C. Atmospheric electricity in high latitudes. Phil. Trans. R. Soc., A, **205,** 61–97 (1905).

[517] Simpson, G. C. Some problems of atmospheric electricity. Monthly Weath. Rev., **44,** 115–122 (1916).

[518] Süring, R. Luft- und Wolkenelektrizität. Lehrbuch der Meteorologie, von J. von Hann. 4. Aufl. herausgegeben von R. Süring, 750–767 (1926).

[519] Swann, W. F. G. On the origin and maintenance of the Earth's charge. Terr. Mag., **20,** 105–126 (1915).

[520] Swann, W. F. G. Atmospheric electricity. Encyclopaedia Britannica, 14th ed., **8,** 217–227 (1929). See also corresponding article by C. Chree in 11th ed., **2,** 860–870 (1910).

[521] Torreson, O. W. The electric characterization of days at the Huancayo Magnetic Observatory for the twelve years 1925–1936. Terr. Mag., **43,** 149–153 (1938).

[522] Whipple, F. J. W. The electrical characterization of days—the practice of the British Meteorological Office. Terr. Mag., **42,** 129–136 (1937).

[522-*A*] Whipple, F. J. W. Modern views on atmospheric electricity. Q. J. R. Met. Soc., **64,** 199–213 (1938). [Presidential address, Royal Meteorological Society, Jan. 19, 1938.]

[523] Wigand, A. Die Erhaltung der Erdladung durch den Blitzstrom. Physik. Zs., **28,** 65–69, 261–263 (1927).

[524] Wilson, C. T. R. Atmospheric electricity. Dictionary of Applied Physics, edited by Sir Richard Glazebrook, **3,** 84–107 (1923).

(2) Observations

[525] Ansel, A. Die luftelektrischen und meteorologischen Ergebnisse der Beobachtungen in Island vom 10. Mai bis 2. Juni 1910 anlässlich des Durchganges des Halleyschen Kometen. Göttingen, Nachr. Ges. Wiss., Math.-physik. Kl., 76–111 (1912).

[526] Ault, J. P., and S. J. Mauchly. Atmospheric-electric results obtained aboard the *Carnegie* 1915–1921. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. No. 175, **5,** 197–286 (1926).

[527] Bauer, L. A., and W. F. G. Swann. Results of atmospheric-electric observations made aboard the *Galilee* (1907–1908) and the *Carnegie* (1909–1916). Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. No. 175, **3**, 361–422 (1917).

[528] Běhounek, F. Atmospheric-electric researches made in 1928 during the Nobile Arctic Expedition in collaboration with Professor A. Pontremoli (Milan) and Professor F. Malmgren (Upsala). Terr. Mag., **34**, 173–198 (1929).

[529] Berndt, G. Luftelektrische Beobachtungen in Argentinien. Berlin, Veröff. D. Wiss. Ver., in Buenos Aires, No. 3, 68 pp. (1913). See also Physik. Zs., **12**, 1125–1129 (1911); **13**, 151–152, 514–516, 775–776, 820–825 (1912).

[530] Brommer, A. Das atmosphärische Potentialgefälle in Triest nach den Beobachtungen von November 1902 bis März 1905. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **118**, 629–701 (1909).

[531] Brommer, A. Luftelektrische Messungen während der Sonnenfinsternis am 17. April 1912. Physik. Zs., **13**, 684–686 (1912).

[532] Dobson, G. Atmospheric electricity observations made at Kew Observatory. London, Proc. Phys. Soc., **26**, 334–346 (1914).

[533] Gish, O. H. The significance of atmospheric-electric observations at sea. Trans. Amer. Geophys. Union, 10th and 11th Annual Meetings, 190–197 (1930).

[534] Gockel, A. Luftelektrische Beobachtungen im schweizerischen Mittelland, im Jura und in den Alpen. Neue Denkschr. Schweiz. Naturf. Ges., **54**, 75 pp. (1917).

[535] Hess, V. F., and W. Kosmath. Luftelektrische Messungen im Innsbrucker Mittelgebirge. Beitr. Geophysik, **36**, 439–451 (1932).

[536] Hewlett, C. W. The atmospheric-electric observations made on the second cruise of the *Carnegie*. Terr. Mag., **19**, 127–170 (1914).

[537] Johnston, H. F., and G. R. Wait. Atmospheric-electric survey in the vicinity of Washington, D. C. Terr. Mag., **36**, 33–40 (1931).

[538] Kidson, E. Atmospheric electricity observations on the first cruise of the *Carnegie*. Terr. Mag., **15**, 83–91 (1910). Atmospheric electricity observations on the second cruise of the *Carnegie* from New York to Colombo. Terr. Mag., **16**, 237–242 (1911).

[539] Knoche, W., and J. Laub. Meteorologische und luftelektrische Messungen während der totalen Sonnenfinsternis am 10. Oktober 1912 auf der Facenda Boã Vista bei Christina (Prov. Minas Geraes—Brasilien). Terr. Mag., **21**, 117–144; 177–204 (1916).

[540] Lautner, P. Die luftelektrischen Verhältnisse am Zugspitzgipfel in 2960 m. D. Met. Jahrb. für Bayern 1928, 1–19 (1929). [Abstract, Met. Zs., **46**, 403–404 (1929).]

[541] Lüdeling, G. Die luftelektrischen Messungen ausgeführt von A. Wegener auf der Danmark-Expedition 1906–1908. Köbenhavn, Danmark-Ekspeditionen til Grönlands Nordöstkyst 1906–1908, **2**, 79–111 (1911).

[542] Mauchly, S. J., and A. Thomson. Results of atmospheric-electric observations made at Sobral, Brazil, during the total solar eclipse of May 29, 1919. Terr. Mag., **25**, 41–48 (1920).

[543] Nolan, J. J., and P. J. Nolan. Preliminary account of observations on atmospheric electricity in country air. Beitr. Geophysik, **25**, 414–428 (1930).

[544] Rouch, J. Observations d'électricité atmosphérique faites dans l'Antarctique pendant l'expédition Charcot (1909). (Deuxième Expédition Antarctique Française, Sciences physiques, Documents Scientifiques.) Paris, Masson et Cie, 39 pp., map, 7 pls. (1913).

[545] Scholz, J. Luftelektrische Messungen auf Franz-Josefs-Land während des II Internationalen Polarjahres 1932–33. Leningrad, Trans. Arctic Inst., **16,** 169 pp. (1935).

[546] Schweidler, E. Luftelektrische Beobachtungen zu Mattsee. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **111,** 1463–1488 (1902); **112,** 1501–1531 (1903); **114,** 1705–1735 (1905).

[547] Schweidler, E. Zusammenfassender Bericht über die Beobachtungen an der luftelektrischen Station Seeham in den Sommern 1908 bis 1915. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **125,** 997–1076 (1916); **126,** 1009–1035 (1917).

[548] Schweidler, E. Zusammenfassender Bericht über die Beobachtungen an der luftelektrischen Station Seeham in den Sommern 1916 bis 1920. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **129,** 919–927 (1920).

[549] Sherman, K. L. Atmospheric electricity at the College-Fairbanks Polar Year Station. Terr. Mag., **42,** 371–390 (1937).

[550] Simpson, G. C., and C. S. Wright. Atmospheric electricity over the ocean. Proc. R. Soc., A, **85,** 175–199 (1911).

[551] Swann, W. F. G. The atmospheric-electric observations on the third cruise of the *Carnegie*, 1914. Report and discussion. Terr. Mag., **20,** 13–48 (1915).

(*b*) *Instruments and methods of measurement*

[552] Aitken, J. Collected scientific papers of John Aitken (with introductory memoir by Cargill G. Knott). Cambridge, University Press, xxi + 591 pp. (1923). [Preliminary study of fog, mist, and clouds and the rôle played by dust-particles as condensation-nuclei in the formation of water-droplets together with development of instruments for determining the number of condensation-nuclei present in the atmosphere.]

[553] Benndorf, H. Über ein mechanisch registrierendes Elektrometer für luftelektrische Messungen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **111,** 487–512 (1902); Physik. Zs., **7,** 98–101 (1906).

[554] Benndorf, H. Zur Theorie luftelektrischer Registrierungen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **118,** 1173–1205 (1909).

[555] Bronson, H. L. Radioactive measurements by a constant deflection method. Amer. J. Sci., **19,** 185–187 (1905). [High-resistance unit later modified by Swann and Mauchly for atmospheric-electric work.]

[556] Ebert, H. Galvanometrische Messung des elektrischen Ausgleichs zwischen den Ionenladungen der Atmosphäre und der Ladung der Erdoberfläche. Physik. Zs., **3,** 338–339 (1902). [First attempt to measure directly the vertical conducting current.]

[557] Ebert, H. Ein Quadrantenelektrometer für luftelektrische Registrierungen. Zs. Instrumentenk., **29,** 169–178 (1909).

[558] Gerdien, H. Demonstration eines Apparates zur absoluten Messung der elektrischen Leitfähigkeit der Luft. Physik. Zs., **6,** 800–801 (1905). [Fuller details in Göttingen, Nachr. Ges. Wiss., 240, 258, 447 (1905).]

[559] Gerdien, H. Die absolute Messung der specifischen Leitfähigkeit und der Dichte des verticalen Leitungsstromes in der Atmosphäre. Terr. Mag., **10,** 65–79 (1905). [Theory of Gerdien method of measuring conductivity.]

[560] Gish, O. H. Systematic errors in measurements of ionic content and the conductivity of the air. Beitr. Geophysik, **35,** 1–5 (1932).

[561] Gish, O. H., and K. L. Sherman. A leak-free method of measuring air-potentials. Terr. Mag., **34,** 231–237 (1929); **42,** 285–288 (1937).

[562] Greinacher, H., and W. Klein. Über einen Apparat zur Dauerregistrierung der spezifischen Ionenzahl der Atmosphäre. Beitr. Geophysik, **51**, 298–307 (1937).

[563] Hoffmann, K. Experimentelle Prüfung der durch verschiedene Messungsanordnungen in einem homogenen elektrischen Felde hervorgerufenen Störungen (Deformationen) der Niveauflächen. München, Dissertation, Tech. Hochschule, 67 pp., 12 Tafeln (1911).

[564] Langevin, P. Sur un enregistreur des ions de l'atmosphère. C.-R. Acad. sci., **140**, 305–307 (1905).

[565] Lejay, P. Sur un électromètre à lampe triode et son application à la mesure du gradient électrique de l'atmosphère. C.-R. Acad. sci., **178**, 1480–1482, 2171–2173 (1924). [See also *ibid.*, **182**, 1634–1635 (1926).]

[566] Lutz, C. W. Über einen neuen Flammenkollektor und dessen Prüfung im elektrischen Felde. München, SitzBer. Ak. Wiss., **36**, 507–525 (1906).

[567] Lutz, C. W. Über ein Saitenelektrometer. Physik. Zs., **9**, 100–107 (1908); **24**, 166–170, 460–462 (1923).

[568] Lutz, C. W. Aufzeichnung der elektrischen Leitfähigkeit der Luft. Beitr. Geophysik, **47**, 241–251 (1936).

[569] Mauchly, S. J. A rotary slide-wire for producing uniform variation in potential difference. J. Optical Soc. Amer. and Rev. Sci. Instr., **6**, 852–858 (1922).

[570] Mauchly, S. J. The atmospheric-electric instrumental equipment for the observatories of the Department of Terrestrial Magnetism. Carnegie Inst. Wash., Year Book, No. 21, 302–304 (1923).

[571] Mauchly, S. J. Control of ionium collectors used in potential-gradient registrations at the observatories of the Department of Terrestrial Magnetism. Carnegie Inst. Wash., Year Book, No. 25, 227 (1926).

[572] Mauchly, S. J. A modified Dolezalek quadrant electrometer for the photographic registration of the potential-gradient of the air. Carnegie Inst. Wash., Year Book, No. 25, 228 (1926).

[573] Owens, J. S. Automatic filter. London, Met. Office, Adv. Comm. Atmos. Pollution, Rep. Obsns. 1917–1918, 20–23 (1919). [Description of filter designed for quantitative measurement of atmospheric suspensoids that affect atmospheric electricity.]

[574] Owens, J. S. Jet-apparatus for the isolation and examination of atmospheric dust. London, Met. Office, Adv. Comm. Atmos. Pollution, Rep. Obsns. 1921–1922, 34–42 (1923).

[575] Riecke, E. Beiträge zu der Lehre von der Luftelektrizität. Ann. Physik, **12**, 52–84 (1903). [Theory underlying measurements with Gerdien conductivity-apparatus.]

[576] Russeltvedt, N. Instrumente und Apparate für die luftelektrischen Untersuchungen an dem Meteorologischen Observatorium in Ås. Oslo, Beiheft Jahrb. Met. Inst. für 1925, 25 pp. (1926). [Contains description of a mechanical collector.]

[577] Scholz, J. Ein neuer Apparat zur Bestimmung der Zahl der geladenen und ungeladenen Kerne. Zs. Instrumentenk., **51**, 505–522 (1931).

[578] Scholz, J. Über die Messmethoden der elektrischen Leitfähigkeit der Atmosphäre. Physik. Zs., **32**, 130–139 (1931).

[579] Smirnow, D. Ein rasch wirkender Wasserkollektor. Physik. Zs., **5**, 597–599 (1904). [See also *ibid.*, **8**, 672–674 (1907); **14**, 1148–1151 (1913).]

[580] Swann, W. F. G. The theory of electrical dispersion into the free atmosphere, with a discussion of the theory of the Gerdien conductivity-apparatus, and of the

theory of the collection of radioactive deposit by a charged conductor. Terr. Mag., **19,** 81–92 (1914).

[581] Swann, W. F. G. On certain new atmospheric-electric instruments and methods. Terr. Mag., **19,** 171–185 (1914).

[582] Swann, W. F. G. On certain matters relating to the theory of atmospheric-electric measurements. Terr. Mag., **19,** 205–218 (1914).

[583] Thomson, W. Description of Lord Kelvin's water-dropper collector. [Extract from Manchester, Proc. Lit. Phil. Soc., Oct. 18, 1859.] Quoted in W. Thomson, Reprint of papers on electrostatics and magnetism, 2d ed., 200–203, London, Macmillan & Company, Ltd. (1884).

[584] Torreson, O. W., and G. R. Wait. Measurements of total nuclei, of uncharged nuclei, and of large ions in the free atmosphere at Washington, D. C. Terr. Mag., **39,** 47–64 (1934).

[585] Wait, G. R. The Aitken pocket nuclei-counter. Beitr. Geophysik, **37,** 429–439 (1932).

[586] Wait, G. R. Report on ion-counters, methods of use, and results. C.-R. Assemblée de Lisbonne, 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 143–147 (1934).

[587] Weger, N. Eine Verbesserung der Methodik der Kleinionen-Zählung. Physik. Zs., **36,** 15–20 (1935). [See also Met. Zs., **54,** 487–488 (1937).]

[588] Wigand, A., and T. Schlomka. Die Messung elektrischer Spannungen vom Motorluftfahrzeug aus. Ann. Physik, **75,** 279–325 (1924).

[589] Wilson, C. T. R. On a portable gold-leaf electrometer for low or high potentials and its application to measurements in atmospheric electricity. Cambridge, Proc. Phil. Soc., **13,** 184–189 (1905). [See also *ibid.,* 363–382 (1906). For account of measurements with this apparatus see Proc. R. Soc., A, **80,** 537–547 (1908).]

[590] Wulf, Th. Ein neues Elektrometer für statische Ladungen. Physik. Zs., **8,** 246–248, 527–530, 780–781 (1907).

[591] Wulf, Th. Über die in der Atmosphäre vorhandene Strahlung von hoher Durchdringungsfähigkeit. Physik. Zs., **10,** 152–157 (1909). [Includes description of bifilar mountings.]

[592] Wulf, Th. Ein Einfadenelektrometer. Physik. Zs., **15,** 250–254 (1914).

(*c*) *Potential-gradient and space-charge*

[593] Angenheister, G. Die luftelektrischen Beobachtungen am Samoa-Observatorium 1914–1918. Göttingen, Nachr. Ges. Wiss., 81–104 (1924).

[594] Angenheister, G. Die Wirkung des Regens auf die Registrierung des Potentialgefälles der Atmosphäre. Göttingen, Nachr. Ges. Wiss., Math.-phys. Kl., 105–115 (1924).

[595] Bauer, L. A. Sunspot and annual variations of atmospheric electricity, with special reference to the *Carnegie* observations, 1915–1921. Res. Dep. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **5,** 359–384 (1926).

[596] Benndorf, H. Über die Störungen des normalen atmosphärischen Potentialgefälles durch Bodenerhebungen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **110,** 923–940 (1900).

[597] Benndorf, H. Über gewisse Störungen des Erdfeldes mit Rücksicht auf die Praxis luftelektrischer Messungen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **115,** 425–456 (1906).

[598] Benndorf, H. Zur Raumladungsmessung in der freien Atmosphäre. Physik. Zs., **27,** 576–578 (1926). [Points out error in space-charge measurements by the

cage-method. Owing to the potential-difference between materials of the cage and the probe, a space-charge will be indicated where none exists. Details are given of the values of the error for different materials.]

[599] Brown, J. G. The relation of space-charge and potential-gradient to the diurnal system of convection in the lower atmosphere. Terr. Mag., **35,** 1–15 (1930).

[599-*A*] Brown, J. G. The rôle of the space-charge in atmospheric electricity. Terr. Mag., **38,** 161–173 (1933).

[600] Daunderer, A. Luftelektrische Messungen. Physik. Zs., **8,** 281–286 (1907). [Change of potential-gradient with altitude.]

[601] Daunderer, A. Über die in den unteren Schichten der Atmosphäre vorhandene freie elektrische Raumladung. Met. Zs., **26,** 301–311 (1909); Physik. Zs., **10,** 113–118 (1909). [Abstracts from author's dissertation, Techn. Hochschule, München (1908).]

[602] Everling, E. Messungen des elektrischen Spannungsgefälles in der freien Atmosphäre bei 9000 m Höhe. Verh. D. phys. Ges., **16,** 240–244 (1914).

[603] Everling, E., and A. Wigand. Spannungsgefälle und vertikaler Leitungsstrom in der freien Atmosphäre, nach Messungen bei Hochfahrten im Freiballon. Ann. Physik, **66,** 261–282 (1921). [Inhalt: 1. Aufgabe; 2. Messverfahren für das Spannungsgefälle; 3. Ergebnisse der Messungen; 4. Erörterung der Ergebnisse, (*a*) normaler vertikaler Verlauf des Spannungsgefälles, (*b*) zeitlicher Verlauf und Störungen an Schichtgrenzen, (*c*) vertikaler Leitungsstrom; 5. Aufgaben für die Weiterarbeit; 6. Zusammenfassung.]

[604] Gerdien, H. Der Elektrizitätshaushalt der Erde und der unteren Schichten der Atmosphäre. Physik. Zs., **6,** 647–666 (1905).

[605] Kähler, K. Die elektrische Raumladung der Atmosphäre in Potsdam. Met. Zs., **44,** 1–5 (1927). [See also *ibid.*, **39,** 293–298 (1922); **40,** 204–211 (1923).] [Measurements by Lord Kelvin's wire-cage method.]

[606] Kähler, K., and C. Dorno. Messungen der elektrischen Raumladung der Atmosphäre in Davos. Met. Zs., **42,** 434–439 (1925).

[607] Lutz, C. W. Aufzeichnung der elektrischen Raumladung der Luft. Beitr. Geophysik, **41,** 416–428 (1934); **52,** 344–376 (1938).

[608] Mauchly, S. J. Studies in atmospheric electricity based on observations made on the *Carnegie*, 1915–1921. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. 175, **5,** 385–424 (1926). [See also Phys. Rev., **18,** 161–162 (1921); Terr. Mag., **28,** 61–81 (1923).] [Universal-time component.]

[609] Norinder, H. Researches on the height variation of the atmospheric-electric potential-gradient in the lowest layers of the air. Geog. Ann., Stockholm, **3,** 1–96 (1921); **4,** 116–121 (1922).

[610] Obolensky, W. N. Über elektrische Ladungen in der Atmosphäre. Ann. Physik, **77,** 644–666 (1925). [Absorption of space-charge by a filter.]

[611] Parkinson, W. C. Some observations of atmospheric-electric potential-gradient on mountain peaks in the Peruvian Andes near Huancayo, Peru. Terr. Mag., **33,** 15–22 (1928).

[612] Rudge, W. A. D. On the electrification produced during the raising of a cloud of dust. Proc. R. Soc., A, **90,** 256–272, 571–582 (1914). [See also Phil. Mag., **25,** 481–494 (1913) where references to author's earlier papers will be found.]

[613] Scrase, F. J. Some measurements of the variation of potential-gradient with height near the ground at Kew Observatory. London, Met. Office, Geophys. Mem., No. 67, 12 pp. (1935).

[614] Stäger, A. Experimentaluntersuchungen über Kontaktelektrisierung von staub- und wolkenförmig zerteilten Körpern, speziell von Schnee als gewitterbildendem

Faktor. Ann. Physik, **76,** 49–70 (1925); **77,** 225–240 (1925). [See also *ibid.*, **77,** 71–80 (1925).] [Contains a good bibliography.]

[615] Sverdrup, H. U. Observations of the atmospheric-electric potential-gradient, 1922–1925. Res. Dept. Terr. Mag., Carnegie Inst. Wash., Pub. No. 175, **6,** 425–460 (1927). [Report of work accomplished on the *Maud* Expedition.]

[616] Swann, W. F. G. The atmospheric potential-gradient, and a theory as to the cause of its connection with other phenomena in atmospheric electricity, together with certain conclusions as to the expression for the electrical force between two parallel charged plates. Terr. Mag., **18,** 163–184 (1913).

[617] Tuma, J. Luftelektricitätsmessungen im Luftballon. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **108,** 227–260 (1899).

[618] Wait, G. R., and H. U. Sverdrup. Preliminary note on electromotive forces produced by the Earth's rotating magnetic field and on observed diurnal-variation of the atmospheric potential-gradient. Terr. Mag., **32,** 73–83 (1927).

[619] Watson, R. A. Electric potential-gradient measurements at Eskdalemuir, 1913–23. London, Met. Office, Geophys. Mem., No. 38, 16 pp. (1928). [The method of measurement, potential-gradient on quiet days, wind and potential-gradient.]

[620] Whipple, F. J. W. Potential-gradient and atmospheric pollution: The influence of "summer time." Q. J. R. Met. Soc., **55,** 351–360 (1929).

[621] Whipple, F. J. W., and F. J. Scrase. Point discharge in the electric field of the Earth. An analysis of continuous records obtained at Kew Observatory. London, Met. Office, Geophys. Mem., No. 68, 20 pp. (1936). [Description of apparatus, typical records, connection between point-discharge current and potential-gradient, lightning-discharges, space-charge blanket, point-discharge as a factor in the circulation of electricity through the atmosphere.]

[622] Wigand, A. Messungen des luftelektrischen Potentialgefälles vom Luftschiff aus. Ann. Physik, **85,** 333–361 (1928).

(*d*) *Conductivity, ion-mobility, etc.*

[623] Behacker, M. Zur Berechnung des Erdfeldes unter der Voraussetzung homogener Ionisierung der Atmosphäre. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **119,** 675–684 (1910).

[624] Berndt, G. Ionengehalt der Luft auf dem Atlantischen Ozean. Met. Zs., **30,** 606–607 (1913).

[625] Booij, J. Messungen des Ionenspektrums in Innsbruck. Beitr. Geophysik, **37,** 167–174 (1932).

[626] Boylan, R. K. Atmospheric dust and condensation nuclei. Proc. R. Irish Acad., A, **37,** 58–70 (1926).

[627] Builder, G. The effect of condensation-nuclei in atmospheric-electric observations. Terr. Mag., **34,** 281–286 (1929).

[628] Conrad, V. Über den täglichen Gang der elektrischen Zerstreuung auf dem Sonnblick. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **113,** 1143–1157 (1904).

[629] Gerdien, H. Die Kondensation des Wasserdampfes an Ionen und ihre Bedeutung für die Physik der Atmosphäre. Jahrb. Radioakt. Elektronik, **1,** 24–39 (1904).

[630] Gerdien, H. Messungen der Dichte des vertikalen elektrischen Leitungsstromes in der freien Atmosphäre bei der Ballonfahrt vom 30, VIII. 1905. Göttingen, Nachr. Ges. Wiss., 447–458 (1905).

[631] Gish, O. H., and K. L. Sherman. Electrical conductivity of air to an altitude of 22 kilometers. Nation. Geog. Soc., Contrib. Tech. Papers, Stratosphere Ser., No. 2, 94–116 (1936).

[632] Gish, O. H., and K. L. Sherman. Information to be obtained from some atmospheric-electric measurements in the stratosphere. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 382–395 (1937).

[633] Hess, V. F. Die elektrische Leitfähigkeit der Atmosphäre und ihre Ursachen. Braunschweig, Vieweg, viii + 174 pp. (1926). English translation under title of "The electrical conductivity of the atmosphere and its causes" by L. W. Codd. London, Constable & Co., Ltd., New York, D. Van Nostrand Company, Inc. xviii + 204 pp. (1928).

[634] Hess, V. F. Die Ionenerzeugung und Ionenvernichtung in der Atmosphäre über dem Meere und im Gebirge. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **136**, 603–643 (1927).

[635] Hess, V. F. Die mittlere Lebensdauer der leichten Ionen und die Ionisierungsbilanz in der Atmosphäre über dem Meere und im Gebirge. Physik. Zs., **28**, 882–894 (1927); **29**, 849–851 (1928).

[636] Hess, V. F. Neue Untersuchungen über die Ionisierungsbilanz der Atmosphäre auf Helgoland. Beitr. Geophysik, **22**, 256–314 (1929). Wien, SitzBer. Ak. Wiss., Abt. II*a*, **138**, 169–221 (1929).

[637] Hess, V. F. Über Zählungen der Kondensationskerne im Innsbrucker Mittelgebirge. Beitr. Geophysik, **28**, 129–150 (1930).

[638] Hess, V. F. Die Ionisierungsbilanz der Atmosphäre. Ergebnisse der kosmischen Physik, **2**, 95–152 (1933).

[639] Hess, V. F., and G. v. Sensel. Messungen des Ionengehaltes der Atmosphäre in den Donauauen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **120**, 137–158 (1911).

[640] Hogg, A. R. Atmospheric electric observations. Beitr. Geophysik, **41**, 1–31 (1934). [Observations at Canberra, Australia, January, 1930 to June, 1932.]

[641] Hogg, A. R. Some observations of the average life of small ions and atmospheric ionisation equilibria. Beitr. Geophysik, **41**, 32–55 (1934).

[642] Hogg, A. R. Continuous observations of the rate of production of small ions in the atmosphere. Beitr. Geophysik, **43**, 359–378 (1935).

[643] Hogg, A. R. The mobility of the small ions of the atmosphere. Beitr. Geophysik, **47**, 31–59 (1936).

[644] Israël, H. Versuche zur Erklärung der Staubelektrisierung. Zs. Tech. Physik, **9**, 289–293 (1928).

[645] Israël, H. Untersuchungen über schwere Ionen in der Atmosphäre. (Erste Mitteilung.) Beitr. Geophysik, **23**, 144–166 (1929).

[646] Israël, H. Schwere Ionen der Atmosphäre. Zs. Geophysik, **7**, 127–133 (1931).

[647] Israël, H. Zur Theorie und Methodik der Grössenbestimmung von Luftionen. Beitr. Geophysik, **31**, 173–216 (1931); **36**, 24–37 (1932).

[648] Israël, H., and L. Schulz. Über die Grössenverteilung der atmosphärischen Ionen. Met. Zs., **49**, 226–233 (1932).

[649] Kennedy, H. The large ions and condensation-nuclei from flames. Proc. R. Irish Acad., A, **33**, 58–74 (1916).

[650] Langevin, P. Sur les ions de l'atmosphère. C.-R. Acad. sci., **140**, 232–234 (1905). [Announcement of discovery of large ions.]

[651] McClelland, J. A., and H. Kennedy. The large ions in the atmosphere. Proc. R. Irish Acad., A, **30**, 72–91 (1912); **32**, 1–6 (1913).

[652] Mazelle, E. Die Zerstreuung der atmosphärischen Elektrizität in Triest und ihre Abhängigkeit von meteorologischen Elementen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **114**, 399–501 (1905).

[653] O'Brolchain, C. The comparison of Schweidler's two methods for determining the average life of small ions in air. Beitr. Geophysik, **29,** 1–21 (1931).

[654] O'Brolchain, C. Measurements made at Graz of the value of $N_0/N_{\pm}$, *i.e.*, the ratio of the number of uncharged nuclei to number of charged nuclei of one sign. Beitr. Geophysik, **38,** 4–15 (1933).

[655] Nolan, J. J. The effect of water vapor on the mobilities of negative ions in air. Proc. R. Irish Acad., A, **39,** 82–99 (1930).

[656] Nolan, P. J. The influence of condensation nuclei and dust particles on atmospheric ionisation. Proc. R. Irish Acad., A, **41,** 61–69 (1933).

[657] Nolan, J. J., R. K. Boylan, and G. P. de Sachy. The equilibrium of ionisation in the atmosphere. Proc. R. Irish Acad., A, **37,** 1–12 (1925).

[658] Nolan, J. J., and V. H. Guerrini. The diffusion coefficients and velocities of fall in air of atmospheric condensation nuclei. Proc. R. Irish Acad., A, **43,** 5–24 (1935).

[659] Nolan, J. J., and J. T. Harris. Ionisation in moist and dry air. Proc. R. Irish Acad., A, **36,** 31–49 (1922).

[660] Nolan, J. J., and P. J. Nolan. Observations on atmospheric ionisation at Glencree, Co. Wicklow. Proc. R. Irish Acad., A, **40,** 11–59 (1931); **41,** 111–128 (1933).

[661] Nolan, J. J., and P. J. Nolan. Atmospheric electrical conductivity and the current from air to Earth. Proc. R. Irish Acad., A, **43,** 79–93 (1937).

[662] Nolan, P. J., and C. O'Brolchain. Recombination of ions in atmospheric air. Proc. R. Irish Acad., A, **38,** 40–59 (1929). [Part I—Investigation of the decay coefficient by Schweidler's method. Part II—The law of recombination of ions and nuclei.]

[663] Nolan, J. J., and J. G. O'Keeffe. Electric discharge from water drops. Proc. R. Irish Acad., A, **40,** 86–98 (1932).

[664] Nolan, J. J., and J. G. O'Keeffe. Multiply charged large ions. Proc. R. Irish Acad., A, **41,** 26–40 (1933).

[665] Nolan, J. J., and G. P. de Sachy. Atmospheric ionisation. Proc. R. Irish Acad., A, **37,** 71–94 (1927).

[666] Noto, N. On electric oscillations in the atmosphere. Jap. J. Astr. Geophys., **7,** 1–29 (1929); **8,** 187–207 (1931).

[667] Pollock, J. A. The nature of the large ions in the air. Phil. Mag., **29,** 514–526 (1915).

[668] Pollock, J. A. A new type of ion in the air. Phil. Mag., **29,** 636–646 (1915). [Refers to intermediate ions.]

[669] Rudge, W. A. D. On the electrification associated with dust-clouds. Phil. Mag., **25,** 481–494 (1913).

[670] Schachl, P. F. Untersuchung über die Zahl der geladenen und ungeladenen Kondensationskerne in Stadt- und Gebirgsluft. Beitr. Geophysik, **38,** 202–219 (1933).

[671] Schlenck, W. Registrierung der elektrischen Leitfähigkeit der Luft in einem Kellerraume. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **131,** 437–443 (1922).

[672] Schlenck, W. Experimentelle Untersuchungen über die Charakteristik des Stromes in schwach ionisierten Gasen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **133,** 29–33 (1924).

[673] Scholz, J. Theoretische Untersuchungen über die Feld- und Ionenverteilung in einem stromdurchflossenen Gas, das auch schwer bewegliche Elektrizitätsträger enthält. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **140,** 49–66 (1931).

[674] Schweidler, E. v. Über die Ionenverteilung in den untersten Schichten der Atmosphäre. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **117,** 653–664 (1908).

[675] Schweidler, E. Über das Gleichgewicht zwischen ionenerzeugenden und ionenvernichtenden Vorgängen in der Atmosphäre. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **127,** 953–967 (1918); **128,** 947–955 (1919).

[676] Schweidler, E. Über die Charakteristik des Stromes in Schwach ionisierten Gasen. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **133,** 23–27 (1924).

[677] Scrase, F. J. The charged and uncharged nuclei in the atmosphere and their part in atmospheric ionization. London, Met. Office, Geophys. Mem., No. 64, 15 pp. (1935). [Methods of observation, tests of apparatus, notation, ratio of numbers of charged and uncharged nuclei, combination coefficients, rate of production of ions at Kew, resistivity, nuclei, and smoke-particles.]

[678] Swann, W. F. G. The measurement of atmospheric conductivity, together with certain remarks on the theory of atmospheric radioactive measurements. Terr. Mag., **19,** 23–37 (1914).

[679] Swann, W. F. G. The theory of electrical dispersion into the free atmosphere, with a discussion of the theory of the Gerdien conductivity apparatus, and of the theory of the collection of radioactive deposit by a charged conductor. Terr. Mag., **19,** 81–92 (1914).

[680] Swann, W. F. G., and S. J. Mauchly. On the conduction of electricity through an ionized gas, more particularly in its relation to Bronson resistances. Terr. Mag., **22,** 1–21 (1917).

[681] Torreson, O. W. On the value of the ratio of the number of uncharged nuclei (N_0) to the number of charged nuclei of one sign ($N_\pm$) at Washington, D. C. Terr. Mag., **39,** 65–68 (1934).

[682] Wait, G. R. Diurnal variation of concentration of condensation-nuclei and of certain atmospheric-electric elements at Washington, D. C. Terr. Mag., **36,** 111–131 (1931).

[683] Wait, G. R. Variations in the small-ion content of the atmosphere and their causes. J. Frank. Inst., **216,** 147–155 (1933).

[684] Wait, G. R. A cause for the decrease in the number of ions in air of occupied rooms. J. Indust. Hygiene, **16,** 147–159 (1934).

[685] Wait, G. R. Computed and observed rates of small-ion production in the atmosphere. Terr. Mag., **40,** 209–214 (1935).

[686] Wait, G. R. People and atmospheric ions. Carnegie Inst. Wash., News Service Bull., **4,** No. 28, 235–240 (1938). [Popular non-technical account.]

[687] Wait, G. R., and O. W. Torreson. Quelques facteurs affectant la conductibilité électrique de l'atmosphère. C.-R. Internat. Electr., Paris, 1932, **12,** 158–167 (1932).

[688] Wait, G. R., and O. W. Torreson. The large-ion and small-ion content of the atmosphere at Washington, D. C. Terr. Mag., **39,** 111–119 (1934). [See also *ibid.*, 65–68 (1934).]

[689] Wait, G. R., and O. W. Torreson. The large-ion and small-ion content of air in occupied rooms. Heating, Piping, and Air Conditioning, **7,** 105–110 (1935).

[690] Wait, G. R., and O. W. Torreson. Diurnal variation of intermediate and large ions of the atmosphere at Washington, D. C. Terr. Mag., **40,** 425–431 (1935).

[691] Watson, R. E. Measurements of the effective electrical conductivity of the air and the Earth's electric field at and near ground level by means of the Wilson universal electrometer. London, Met. Office, Geophys. Mem., No. 45, 23 pp. (1929).

[692] Weiss, R., and R. Steinmaurer. Messungen der Luftionen in Innsbruck. Beitr. Geophysik, **50,** 238–251 (1937).

[693] Whipple, F. J. W. Relations between the combination coefficients of atmospheric ions. Proc. Phys. Soc., **45**, 367–380 (1933).

[694] Wigand, A., and H. Koppe. Messungen des Ionengehalts der Luft im Flugzeuge. Halle, Mitt. natf. Ges., **6**, 3–14 (1921).

[695] Wright, H. L. Observations of smoke particles and condensation nuclei at Kew Observatory. London, Met. Office, Geophys. Mem., No. 57, 22 pp. (1932).

[696] Wright, H. L. The association between relative humidity and the ratio of the number of large ions to the total number of nuclei. Terr. Mag., **39**, 277–280 (1934).

[697] Wright, H. L. The size of atmospheric nuclei: Some deductions from measurements of the number of charged and uncharged nuclei at Kew Observatory. Proc. Phys. Soc., **48**, 675–689 (1936).

[698] Zölss, B. Messungen der Elektrizitätszerstreuung in Kremsmünster. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **112**, 1117–1222 (1903).

[699] Zölss, B. Elektrizitätszerstreuung in Kremsmünster (1903 bis 1904). Wien, SitzBer. Ak. Wiss., Abt. II*a*, **114**, 189–331 (1905).

(*e*) *Air-earth current*

[700] Carse, G. A., and D. MacOwan. Observations of the earth-air electric current and the atmospheric potential gradient at Edinburgh. Edinburgh, Proc. R. Soc., **30**, 460–465 (1910).

[701] Ebert, H. Galvanometrische Messung des elektrischen Ausgleichs zwischen den Ionenladungen der Atmosphäre und der Ladung der Erdoberfläche. Physik. Zs., **3**, 338–339 (1902). [First attempt to measure with precision the air-earth current.]

[702] Grieger, H. Absolute Messungen des vertikalen Leitungsstromes in Potsdam. Berlin, Emil Ebering, 54 pp. (*ca.* 1934).

[703] Lutz, C. W. Luftelektrische Messungen am Erdmagnetischen Observatorium (Sternwarte) München. München, SitzBer. Ak. Wiss., 305–360 (1911). [I. Registrierung des Potentialgefälles 1905 bis 1910 (pp. 305–328); II. Messung des vertikalen Leitungsstromes Luft-Erde im Jahre 1909 (pp. 329–360).]

[704] Scrase, F. J. The air-earth current at Kew Observatory. Some results obtained with a new automatic recorder. London, Met. Office, Geophys. Mem., No. 58, 22 pp., 7 pls. (1933).

[705] Simpson, G. C. Earth-air electric currents. Phil. Mag., **19**, 715–725 (1910). [An account of observations made at Simla by means of an arrangement for automatically recording the current.]

[706] Wilson, C. T. R. On the measurement of the earth-air current and on the origin of atmospheric electricity. Cambridge, Proc. Phil. Soc., **13**, 363–382 (1906). [See also Nature, **68**, 102–104 (1903).]

[707] Wilson, C. T. R. On the measurement of the atmospheric electrical potential gradient and the earth-air current. Proc. R. Soc., A, **80**, 537–547 (1908).

(*f*) *Electricity of precipitation*

[708] Benndorf, H. Über die Beobachtungen der Niederschlagselektrizität. München, SitzBer. Ak. Wiss., 402–429 (1912). [General survey of the subject with bibliography of original articles.]

[709] Chauveau, A. B. Sur quelques données actuelles relatives à l'électricité de la pluie. (À propos des observations récentes de M. Baldit.) Le Radium, **8**, 153–156 (1911). [For later observations see Baldit, A. Nouvelles observations sur les

charges électriques de la pluie en 1911, au Puy-en-Velay. Le Radium, **9,** 92–101 (1912).]

[710] Elster, J., and H. Geitel. Zur Influenztheorie der Niederschlagselektrizität. Physik. Zs., **14,** 1287–1292 (1913). [See also *ibid.*, **17,** 455–464 (1916) and Wied. Ann., **25,** 116 (1885).]

[711] Elster, J., and H. Geitel. Über eine Methode, die elektrische Natur der atmosphärischen Niederschläge zu bestimmen. Met. Zs., **5,** 95–100 (1888). Beobachtungen, betreffend die elektrische Natur der atmosphärischen Niederschläge. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **99,** 421–450 (1890). Beobachtungen über die Eigenelektricität der atmosphärischen Niederschläge. Terr. Mag., **4,** 15–29, 17 figs. (1899).

[712] Gerdien, H. Registrierungen der Niederschlagselektrizität im Göttinger Geophysikalischen Institut. Physik. Zs., **4,** 837–842 (1903).

[713] Gott, J. P. On the electric charge collected by water drops falling through ionized air in a vertical electric field. Proc. R. Soc., A, **142,** 248–268 (1933); **151,** 665–684 (1935).

[714] Gott, J. P. Phenomena attending the splashing of water in an electric field. Cambridge, Proc. Phil. Soc., **31,** 85–93 (1935).

[715] Gschwend, P. P. Beobachtungen über die elektrischen Ladungen einzelner Regentropfen und Schneeflocken. Sarnen, 55 pp. (1922). [Beilage zum Jahresbericht der kantonalen Lehranstalt in Sarnen pro 1921/22. Contains bibliography.]

[716] Lenard, P. Über Wasserfallelektrizität und über die Oberflächenbeschaffenheit der Flüssigkeiten. Ann. Physik, **47,** 463–524 (1915); **65,** 629–639 (1921). [See also Met. Zs., **21,** 249–262 (1904).]

[717] Macky, W. A. Some investigations on the deformation and breaking of water drops in strong electric fields. Proc. R. Soc., A, **133,** 565–587 (1931). [See also Proc. R. Irish Acad., A, **40,** 86–98 (1932).]

[718] McClelland, J. A., and J. J. Nolan. The electric charge on rain. Proc. R. Irish Acad., A, **29,** 81–91 (1912); **30,** 61–71 (1912). [See also *ibid.*, **35,** 13–29 (1920).]

[719] Nakaya, U., and T. Terada. On the electrical nature of snow particles. Sapporo, J. Faculty Sci., Hokkaido Imp. Univ., Ser. 2, **1,** 181–190 (1934).

[720] Nolan, J. J. The breaking of water-drops by electric fields. Proc. R. Irish Acad., **37,** 28–39 (1926). Reprinted in Beitr. Geophysik, **15,** 304–316 (1926).

[721] Nolan, J. J., and J. G. O'Keeffe. Electric discharge from water-drops. Proc. R. Irish Acad., A, **40,** 86–98 (1932).

[722] Nukiyama, D., and H. Noto. On the electrification of water-drops. Jap. J. Astr. Geophys., **6,** 41–61 (1928).

[723] Schindelhauer, F. Über die Elektrizität der Niederschläge. Berlin, Veröff. Met. Inst., No. 263 (Abh. **4,** No. 10), 51 pp. (1913).

[723-*A*] Scrase, F. J. Electricity on rain. A discussion of records obtained at Kew Observatory, 1935–6. London, Met. Office, Geophys. Mem., No. 75, 20 pp. (1938).

[724] Simpson, G. C. On the electricity of rain and its origin in thunder-storms. Phil. Trans. R. Soc., A, **209,** 379–413 (1909). [This paper is divided into three parts: I. Measurements of the electricity of the rain; II. Laboratory experiments; III. Theoretical conclusions.] [See also Proc. R. Soc., A, **82,** 169–172 (1909); **83,** 394–404 (1910); Physik. Zs., **14,** 1057–1066 (1913).]

[725] Simpson, G. C. On the electricity of rain and snow. Proc. R. Soc., A, **83,** 394–404 (1910).

[726] Simpson, G. C. The electricity of atmospheric precipitation. Phil. Mag., **30,** 1–12 (1915).

[727] Zeleny, J. Variation with temperature of the electrification produced in air by the disruption of water-drops and its bearing on the prevalence of lightning. Phys. Rev., **44,** 837–842 (1933).

(*g*) *Thunder-storms and lightning*

[728] Alexander, W. H. The distribution of thunderstorms in the United States. Mon. Weath. Rev., **52,** 337–343 (1924).

[729] Banerji, S. K. The electric field of overhead thunderclouds. Phil. Trans. R. Soc., A, **231,** 1–27 (1932). [See also Q. J. R. Met. Soc., **56,** 305–331 (1930).]

[730] Boys, C. V. Progressive lightning. Nature, **118,** 749–750 (1926); **122,** 310–311 (1928).

[731] Brand, W. Der Kugelblitz. Hamburg, Henri Grand, 170 pp. (1923).

[732] Brasch, A., und F. Lange. Experimentell-technische Vorbereitungen zur Atomzertrümmerung mittels hoher elektrischer Spannungen. Zs. Physik, **70,** 10–37 (1931).

[733] British National Committee. Atmospheric electricity. Trans. Edinburgh Meeting 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 104–109 (1937). [Contains among other items brief description of novel method of studying the field below as well as above a thunder-cloud.]

[734] Brooks, C. E. P. The distribution of thunderstorms over the Globe. London, Met. Office, Geophys. Mem., **3,** 145–164 (1925).

[734-*A*] Cravath, A. M., and L. B. Loeb. The mechanism of the high velocity of propagation of lightning discharges. Physics, **6,** 125–127 (1935).

[735] Dorsey, N. E. Lightning. J. Frank. Inst., **201,** 485–496 (1926).

[736] Fortescue, C. L. La foudre et ses effets sur les lignes aériennes. C.-R. Cong. Internat. Electr., Paris, 1932, **6,** 399–464 (1932).

[737] Gockel, A. Das Gewitter. Berlin und Bonn, Ferd. Dümmlers Verlagsbuchhandlung, 3. Aufl., viii + 316 pp. (1925).

[738] Goodlet, B. L. Lightning. J. Inst. Elec. Eng., **81,** 1–26 (1937); discussion, 26–56.

[739] Halliday E. C. The polarity of thunderclouds. Proc. R. Soc., A, **138,** 205–229 (1932).

[740] Halliday, E. C. On the propagation of a lightning discharge through the atmosphere. Phil. Mag., **15,** 409–420 (1933).

[741] Halliday, E. C. Thunderstorms and penetrating radiation. Cambridge, Proc. Phil. Soc., **30,** 206–215 (1934).

[742] Jehle, H. Zur Vorwachsgeschwindigkeit des Blitzes. Zs. Physik, **82,** 785–793 (1933).

[743] Jensen, J. The branching of lightning and the polarity of thunderclouds. J. Frank. Inst., **216,** 707–748 (1933).

[744] Kähler, K. Die Elektrizität der Gewitter. Berlin, Gebrüder Borntraeger, 148 pp. (1924).

[745] Knoche, W. Eine Beobachtung des Leuchtens über den Anden zu Valparaiso. Met. Zs., **26,** 83–84 (1909). [See also *ibid.,* **29,** 87–89, 329–330 (1912); **30,** 311 (1913).]

[746] Laby, T. H., and others. Discussion on thunderstorm researches. Q. J. R. Met. Soc., **62,** 499–527 (1936).

[747] Larsen, Alex. Photographing lightning with a moving camera. Smithsonian Inst., Ann. Rep. for 1905, 119–127, 6 pls. (1906).

[748] Lewis, W. W., and C. M. Foust. Lightning surges on transmission lines—natural lightning. Gen. Elec. Rev., **39**, 543–555 (1936). [Measuring and recording devices, crest-values, attenuation, wave-shape, field-intensity data, current, potential.]

[749] Matthias, A. Der gegenwärtige Stand der Blitzschutzfrage. Elektrot. Zs., **50,** 1469–1474 (1929).

[750] McEachron, K. B., and W. A. McMorris. The lightning stroke. Mechanism of discharge. Gen. Elec. Rev., **39**, 487–496 (1936). [Potentials and field-gradients; wave-shape of discharge and the current-flow; leader and main strokes; multiple strokes; photographic records and their interpretation.]

[751] Norinder, H. Die Blitzentladungen als Ursache atmosphärischer Rundfunkstörungen. Elektr. Nachr.-Technik, **9**, 195–201 (1932).

[752] Norinder, H. Lightning currents and their variations. J. Frank. Inst., **220,** 69–92 (1935). [See also *ibid.*, **205,** 747–765 (1928); **218,** 717–738 (1934).]

[753] Nukiyama, D., and H. Noto. A contribution on the charges of thunderclouds. Jap. J. Astr. Geophys., **6**, 71–81 (1928).

[754] Ollendorff, F. Der Einfluss des Erdwiderstandes auf den Blitz. Physik. Zs., **33,** 368–376 (1932).

[755] Ollendorff, F. Versuch einer Theorie der Blitzsäule. Arch. Electrot., **27**, 169–184 (1933).

[756] Peek, F. W., Jr. Lightning. J. Frank. Inst., **199**, 141–182 (1925).

[757] Peters, O. S. Protection of life and property against lightning. Washington, D. C., Bur. Stan., Tech. Paper, No. 56, 127 pp. (1915). (App. III, pp. 126–127, contains a list of books and papers on lightning-rods.)

[758] Pittman, R. R., and J. J. Torok. Lightning investigation on a wood-pole transmission line. Trans. Amer. Inst. Elec. Eng., **50,** 568–573 (1931).

[759] Pockels, F. Über die bei Blitzentladungen erreichte Stromstärke. Physik. Zs., **2,** 306–307 (1901); **3,** 22–23 (1901).

[760] Pockels, F. Ein Versuch, die bei Blitzschlägen erreichte maximale Stromstärke zu schätzen. Met. Zs., **15,** 41–46 (1898); **18,** 40–41 (1901).

[761] Rüdenberg, R. Die Kopfgeschwindigkeit elektrischer Funken und Blitze. Wiss. Veröff. Siemens-Konz., **9,** I, 1–6 (1930).

[762] Schmidt, K. E. F. Beobachtungen über die Leuchtdauer der Blitze. Elektrot. Zs., **26,** 903–904 (1905).

[763] Schonland, B. F. J. The polarity of thunderclouds. Proc. R. Soc., A, **118,** 233–251 (1928).

[764] Schonland, B. F. J. The interchange of electricity between thunderclouds and the Earth. Proc. R. Soc., A, **118,** 252–262 (1928).

[765] Schonland, B. F. J. Thunderstorms and the penetrating radiation. Proc. R. Soc., A, **130,** 37–63 (1930).

[766] Schonland, B. F. J. The development of the lightning discharge. Trans. S. Afric. Inst. Elec. Eng., **24,** 145–153 (1933).

[767] Schonland, B. F. J. The diameter of the lightning channel. Phil. Mag., **23,** 503–508 (1937).

[768] Schonland, B. F. J. The lightning discharge, being the Halley Lecture delivered on 28 May, 1937. Oxford, Clarendon Press, 19 pp. (1938).

[769] Schonland, B. F. J., and T. E. Allibone. Branching of lightning. Nature, **128,** 794–795 (1931).

[770] Schonland, B. F. J., and collaborators. Progressive lightning. Proc. R. Soc., A, 143, 654–674 (1934); **152,** 595–625 (1935); **162,** 175–203 (1937); **164,** 132–150

(1938); **166,** 56–75 (1938); **168,** 455–469 (1938). [See also Nature, **134,** 177–178 (1934).]

[771] Schonland, B. F. J., and J. Craib. The electric fields of South African thunderstorms. Proc. R. Soc., A, **114,** 229–243 (1927).

[772] Schonland, B. F. J., and D. C. Hodges. The relation between thunderstorms and atmospherics in southern Africa. Trans. R. Soc. S. Africa, **24,** 81–92 (1936).

[773] Schonland, B. F. J., and J. P. T. Viljoen. On a penetrating radiation from thunderclouds. Proc. R. Soc., A, **140,** 314–333 (1933). [See also J. E. I. Cairns, Nature, **132,** 174 (1933) and E. V. Appleton and E. G. Bowen, *ibid,* **132,** 965 (1933).]

[774] Simpson, G. C. On the Wilson-Gerdien theory of thunderstorm electricity. Phil. Mag., **17,** 619–634 (1909).

[775] Simpson, G. C. On lightning. Proc. R. Soc., A, **111,** 56–67 (1926).

[776] Simpson, G. C. The mechanism of a thunderstorm. Proc. R. Soc., A, **114,** 376–401 (1927).

[777] Simpson, G. C. Lightning. J. Inst. Elec. Eng., **67,** 1269–1282 (1929). [The Twentieth Kelvin Lecture delivered before the Institution of Electrical Engineers, April 25, 1929. This lecture, in slightly abridged form, was also published in Nature, **124,** 801–812 (1929).]

[778] Simpson, G. C., and F. J. Scrase. The distribution of electricity in thunderclouds. Proc. R. Soc., A, **161,** 309–352 (1937).

[779] Steadworthy, A. Photographing lightning. J. R. Astr. Soc. Can., **6,** 322–323, 3 pls. (1912).

[780] Toepler, M. Zur Kenntniss der Kugelblitze. Ann. Physik, **2,** 623–635 (1900). Reprinted in Met. Zs., **17,** 543–552 (1900).

[781] Toepler, M. Gewitter, Blitze und Wanderwellen auf Leitungsnetzen. Mitt. Hermsdorf-Schomburg Isolatoren, G.m.b.H., No. 25, 743–786 (1926).

[782] Wait, G. R., and A. G. McNish. Atmospheric ionization near the ground during thunderstorms. Mon. Weath. Rev., **62,** 1–4 (1934).

[783] Walter, B. Über die Entstehungsweise des Blitzes. Ann. Physik, **10,** 393–407 (1903). [See also his later papers, Physik. Zs., **13,** 1082–1084 (1912); **35,** 88–91 (1934).]

[784] Watson Watt, R. A. The present position of theories of the electricity of thunderstorms. Q. J. R. Met. Soc., **57,** 133–142 (1931).

[785] Wilson, C. T. R. On thunderstorm electricity. Phil. Mag., **17,** 634–641 (1909).

[786] Wilson, C. T. R. Investigations on lightning discharges and on the electric field of thunderstorms. Phil. Trans. R. Soc., A, **221,** 73–115 (1920). [See also Proc. R. Soc., A, **92,** 555–574 (1916).]

[787] Wilson, C. T. R. The electric field of a thundercloud and some of its effects. Proc. Phys. Soc., **37,** 32*D*-37*D* (1925).

[788] Wilson, C. T. R. The acceleration of β-particles in strong electric fields such as those of thunderclouds. Cambridge, Proc. Phil. Soc., **22,** 534–538 (1925).

[789] Wilson, C. T. R. Some thundercloud problems. J. Frank. Inst., **208,** 1–12 (1929).

[790] Wormell, T. W. Currents carried by point-discharges beneath thunderclouds and showers. Proc. R. Soc., A, **115,** 443–455 (1927).

[791] Wormell, T. W. Vertical electric currents below thunderstorms and showers. Proc. R. Soc., A, **127,** 567–590 (1930).

[792] Wigand, A. Die Erhaltung der Erdladung durch den Blitzstrom. Physik. Zs., **28,** 65–69, 261–263 (1927).

(*h*) *Aurora*

In this section on the aurora, an attempt has been made to select general papers summarizing the development of research on the subject and those dealing with important investigations and theories advanced. The references contained in the papers cited will guide the reader to further material. Many of the earlier works, now largely superseded and to which reference is seldom made, have been omitted.

[793] Angenheister, G. Das Polarlicht. Müller-Pouillets Lehrbuch der Physik, 11. Aufl., **5**, 1. Hälfte, 485–518 (1928).

[794] Angenheister, G. Die Höhe der Polarlichter und die Temperatur der oberen Atmosphäre. Terr. Mag., **37**, 431–438 (1932).

[795] Angenheister, G. Polarlicht. Handbuch der Naturwissenschaften, 2. Aufl., **8**, 14 pp. (1933).

[796] Angot, A. The Aurora Borealis. London, Kegan Paul, Trench, Trübner and Co., xii + 264 (1896).

[797] Arrhenius, S. Über die Ursache der Nordlichter. Physik. Zs., **2**, 81–87, 97–105 (1900).

[798] Barbier, D. L'émission de particules électrisées par le Soleil et la théorie des aurores polaires. J. Physique et Le Radium, **8**, 303–308 (1937).

[799] Barnard, E. E. Observations of the aurora, made at the Yerkes Observatory, 1902–1909. Astroph. J., **31**, 208–233 (1910).

[800] Birkeland, Kr. Sur la succion des rayons cathodiques vers un pôle magnétique. Arch. Sci. Phys., **1**, 497–512 (1896).

[801] Boller, W. Das Südlicht. Beitr. Geophysik, **3**, 56–130, 550–608 (1898).

[802] Brüche, E. Störmers Polarlichttheorie in Experimenten. Zs. Astroph., **2**, 30–69 (1931). [For other articles dealing with same subject see: Physik. Zs., **31**, 1011–1016 (1930); **32**, 31–33 (1931); Naturw., **18**, 1085–1092 (1930); Terr. Mag., **36**, 41–52 (1931).]

[803] Carlheim-Gyllensköld, V. Aurores boréales. Observations faites au Cap Thordsen, Spitzberg, par l'Expédition Suédoise, publiées par l'Académie Royale des Sciences de Suède. **2**, I, 409 pp., 30 pls. (1886).

[804] Chapman, S. On solar ultra-violet radiation as the cause of aurorae and magnetic storms. Mon. Not. R. Astr. Soc., Geophys. Sup., **2**, 296–300 (1930).

[805] Chapman, S. On the production of auroral and night-sky light. Phil. Mag., **23**, 657–665 (1937).

[806] Chree, C. Aurora Polaris. Encyclopaedia Britannica, 11th ed., **2**, 927–934 (1910).

[807] Currie, B. W. Summary of some auroral height-measurements and observations at Chesterfield, Canada. Terr. Mag., **39**, 293–297 (1934).

[808] Currie, B. W., and H. W. Edwards. On the auroral spectrograms taken at Chesterfield, Canada, during 1932–33. Terr. Mag., **41**, 265–278 (1936).

[809] Davies, F. T. Observations of the aurora australis, Byrd Antarctic Expedition, 1929. Terr. Mag., **36**, 199–230 (1931).

[810] Eve, A. S. Northern lights. Nature, **137**, 813–820 (1936). [Reprinted in Smithsonian Inst.,Rep. for 1936, pp. 145–160 (1937).]

[811] Fritz, H. Verzeichniss beobachteter Polarlichter. Wien, 255 pp. (1873). [Contains "Nordlichte," 503 B.C. to August, 1872 A.D.; and "Südlichte," 1640 to February 4, 1872.]

[812] Fritz, H. Das Polarlicht. Leipzig, Brockhaus, x + 348 pp, 4 pls., 1 map (1881). [This book contains the original map, so frequently reproduced in later publications, showing the geographic distribution of the aurora.]

[813] Fuller, V. R., and E. H. Bramhall. Auroral research at the University of Alaska 1930–1934. Misc. Pub. Univ. Alaska, **3,** 130 pp. (1937). [Chapters 1, 2, and 3, containing reports for 1930–31, 1931–32, 1932–34, are reproduced from Terr Mag., **36,** 297–308 (1931); **37,** 159–166 (1932); **38,** 207–238 (1933); **40,** 269–275 (1935).]

[814] Harang, L. Filteraufnahmen von Polarlicht. Zs. Geophysik, **7,** 324–336 (1931); Geofys. Pub., **10,** No. 8, 27 pp., 3 pls. (1934).

[815] Harang, L., and W. Bauer. Über einen Nordlichtbogen in weniger als 80 km Höhe über der Erde. Beitr. Geophysik, **37,** 109–115 (1932).

[816] Harang, L., and E. Tönsberg. Investigations of the Aurora Borealis at Nordlys Observatoriet, Tromsö, 1929–1930. Geofys. Pub., **9,** No. 5 (1932). [Contains results of height-measurements of the aurora.]

[817] Hewson, E. W. A survey of the facts and the theories of the aurora. Rev. Modern Phys., **9,** 403–431 (1937). [Excellent summary with extensive bibliography.]

[818] Hulburt, E. O. On the diurnal variation of the Aurora Polaris. Terr. Mag., **36,** 23–28 (1931). [Data from many arctic and antarctic expeditions are summarized.]

[819] International Union of Geodesy and Geophysics. Photographic atlas of auroral forms and scheme for visual observations of aurorae. Oslo, A. W. Bröggers Boktrykkeri, 24 pp. with 48 photographic reproductions (1930). [Supplements giving further details regarding observations of aurora, published 1932.]

[820] Johnson, J. H. Concerning the Aurora Borealis. Berkeley, Calif., Gazette Press, 29 pp. (1930). [This publication contains quotations from various writers regarding low-altitude auroras and accompanying sounds, together with the text of 21 letters received by the author in response to a letter requesting information on these two points which was inserted in the newspapers of Alaska and British Yukon Territory.]

[821] Kaplan, J. Active nitrogen and the auroral spectrum. Phys. Rev., **45,** 671–677 (1934). [See also *ibid.*, **33,** 154–156 (1929); **42,** 86–96, 807–811 (1932).]

[822] Lovering, J. On the periodicity of the aurora borealis. Mem. Amer. Acad., **10,** 351 pp. (1868). [Catalogue covers period 502 B.C.–1868 A.D.]

[823] McLennan, J. C. The aurora and its spectrum. Proc. R. Soc., A, **120,** 327–357 (1928). [See also *ibid.*, **108,** 501–512 (1925) and **115,** 515–527 (1927).]

[824] Maris, H. B., and E. O. Hulburt. A theory of auroras and magnetic storms. Phys. Rev., **33,** 412–431 (1929); **34,** 344–351 (1929); **36,** 1560–1569 (1930). [Also Terr. Mag., **33,** 229–231 (1928). Objection to this theory raised by S. Chapman in Mon. Not. R. Astr. Soc., Geophys. Sup., **2,** 296–300 (1930).]

[825] Mawson, D. Auroral observations at the Cape Royds Station, Antarctica, British Antarctic Expedition, 1908. Trans. R. Soc. S. Australia, **40,** 151–212 (1916).

[826] Moltke, H. Forms of auroras. Copenhagen, Dansk Met. Inst., 11 pls. (*ca.* 1930). [This collection consists of 11 colored plates of auroras, reproduced from paintings by Harald Moltke.]

[827] Paulsen, A. Aurores boréales observées à Godthaab (1882–1883). Copenhague, Inst. Met. de Danemark, 73 pp. (1891). [Observations internationales polaires 1882–83. Expédition danoise. Extrait du tome I.]

[828] Paulsen, A. Sur les récentes théories de l'aurore polaire. Kjöbenhavn, Vid. Selsk. Overs., No. 2, 109–144 (1906).

[829] Simpson, G. C. Low auroras. Q. J. R. Met. Soc., **59,** 185–190 (1933). [Discusses the questions: (*a*) Does sound accompany auroral displays? (*b*) Do auroras ever approach near the surface of the Earth?]

[830] Störmer, C. Sur le mouvement d'un point matériel portant une charge d'électricité sous l'action d'un aimant élémentaire. Kristiania, Skr. Vid. selsk., I, No. 3, 32

pp. (1904). [Störmer has published a large number of later mathematical papers dealing with the corpuscular theory of the aurora, a list of which may be found in Terr. Mag., **35**, 207–208 (1930).]

[831] Störmer, C. Sur les trajectoires des corpuscules électriques dans l'espace sous l'influence du magnétisme terrestre, avec application aux aurores boréales et aux perturbations magnétiques. C.-R. Acad. sci., **142**, 1580–1583 (1906); **143**, 140–142, 460–464 (1906).

[832] Störmer, C. Bericht über eine Expedition nach Bossekop zwecks photographischer Aufnahmen und Höhenmessungen von Nordlichtern. Kristiania, Skr. Vid. selsk., I, No. 17, 111 pp., 86 pls. (1911).

[833] Störmer, C. Corpuscular theory of the Aurora Borealis. Terr. Mag., **22**, 23–34, 97–112 (1917).

[834] Störmer, C. Rapport sur une expédition d'aurores boréales à Bossekop et Store Korsnes pendant le printemps de l'année 1913. Geofys. Pub., **1**, No. 5, 269 pp., 104 pls. (1921).

[835] Störmer, C. Résultats des mesures photogrammétriques des aurores boréales observées dans la Norvège méridionale de 1911 à 1922. Geofys. Pub., **4**, No. 7, 107 pp., 48 pls. (1926). [Detailed résumé of photogrammetric measurements of auroras made in southern Norway, 1911–22.]

[836] Störmer, C. On an aurora curtain of violet-gray colour situated at a high altitude photographed on September 8th, 1926. Beitr. Geophysik, **17**, 254–269 (1927); Sonnenbelichtete Nordlichtstrahlen, Zs. Geophysik, **5**, 177–194 (1929), **6**, 463–466 (1930).

[837] Störmer, C. Periodische Elektronenbahnen im Felde eines Elementarmagneten und ihre Anwendung auf Brüches Modellversuche und auf Eschenhagens Elementarwellen des Erdmagnetismus. Zs. Astroph., **1**, 237–274 (1930).

[838] Störmer, C. Twenty-five years' work on the polar aurora. Terr. Mag., **35**, 193–208 (1930).

[839] Störmer, C. Über die Probleme des Polarlichtes. Ergebnisse der kosmischen Physik, **1**, 1–86 (1931). [Latest summary of author's work on the aurora. In the foot-notes are references to many of his previous important papers on the subject.]

[840] Störmer, C. Ein Fundamentalproblem der Bewegung einer elektrisch geladenen Korpuskel im kosmischen Raume. Zs. Astroph., **3**, 31–52, 227–252 (1931); **4**, 290–318 (1932).

[841] Störmer, C. Über die Bahnen von Elektronen im axialsymmetrischen elektrischen und magnetischen Felde. Ann. Physik, **16**, 685–696 (1933).

[842] Tromholt, S. Catalog der in Norwegen bis Juni 1878 beobachteten Nordlichter. Zusammengestellt von Sophus Tromholt. Nach dem Tode des Verfassers . . . herausgegeben von J. Fr. Schroeter. Kristiania, xxiii + 422 pp. (1902). [Date of first observation September 22, 1594.]

[843] Vegard, L. Photographische Aufnahmen des Nordlichtspektrums mit einem Spektrographen von grosser Dispersion. Physik. Zs., **14**, 677–681 (1913). [See also article on aurora of May 13–15, 1921, by Lord Rayleigh, Proc. R. Soc., A, **101**, 114–124 (1922).]

[844] Vegard, L. Bericht über die neueren Untersuchungen am Nordlicht. Jahrb. Radioakt. Elektronik, **14**, 383–465, 6 pls. (1917).

[845] Vegard, L. Recent results of northlight investigations and the nature of the cosmic electric rays. Phil. Mag., **42**, 47–87 (1921).

[846] Vegard, L. Investigations of the auroral spectrum based on observations from the Auroral Observatory, Tromsö. Geofys. Pub., **10**, No. 4, 61 pp., 3 pls. (1933).

[Equipment and plan of work; observations and results; discussion of results. See also Nature, **132,** 682 (1933).]

[847] Vegard, L. The auroral spectrum and the upper strata of the atmosphere. Skr. Vid. selsk., I, Nos. 8, 9, and 10 (1923). [See also Phil. Mag., **46,** 193–211, 577–604 (1923); Zs. Physik, **16,** 367–390 (1923).]

[848] Vegard, L. Nordlicht. Handbuch der Experimentalphysik, herausgegeben von W. Wien und F. Harms, **25,** I, 385–476 (1928).

[849] Vegard, L. Die sonnenbelichteten Nordlichtstrahlen und die Konstitution der höheren Atmosphärenschichten. Zs. Geophysik, **6,** 42–56 (1930); **7,** 196–198 (1931).

[850] Vegard, L. The northern lights and the story they tell. Sci. Prog., **28,** 593–609 (1934). [Popular account.]

[851] Vegard, L., and O. Krogness. The position in space of the Aurora Polaris from observations made at the Haldde-Observatory 1913–1914. Geofys. Pub., **1,** No. 1, 172 pp., 29 pls. (1920).

[852] Westman, J. Aurores boréales. Observations et mesures de l'aurore boréale faites en 1899 et en 1900 à la Baie de Treurenberg, Spitzberg. Missions scientifiques pour la mesure d'un arc de méridien au Spitzberg entreprises en 1899–1902 sous les auspices des gouvernements suédois et russe. Stockholm, Mission suédoise, **2,** Sec. 8, *C,* 114 pp., 7 pls. (1904).

[853] Weyprecht, C. Die Nordlichtbeobachtungen der österreichisch-ungarischen arctischen Expedition 1872–1874. Wien, Denkschr. Ak. Wiss., **35,** 64 pp. (1878). [Contains discussion of all aspects of auroras observed.]

[854] Wright, C. S. Observations on the aurora. London, Harrison & Sons, Ltd., 46 pp. (1921). [Observations discussed were obtained at Cape Evans and Cape Adare by the British (Terra Nova) Antarctic Expedition 1910–1913.]

(*i*) *Earth-currents*

Before the beginning of the present century measurements of earth-currents were made at different times and at different places, usually in connection with telegraph-lines. In 1910, however, systematic observations were inaugurated at the Observatorio del Ebro, Tortosa, Spain, and were continued until interrupted by the civil war in Spain, thus constituting the longest uninterrupted series of earth-current records in existence. Continuous series of earth-current observations have also been in progress at the two magnetic observatories of the Carnegie Institution of Washington, at Watheroo, Western Australia (since 1924), and Huancayo, Peru (since 1927), and at the United States Coast and Geodetic Survey observatory at Tucson, Arizona (since 1931). During the Second International Polar Year 1932–33, similar measurements were carried out at a number of stations, for example, College-Fairbanks, Alaska, Chesterfield, Canada, Sodankylä, Finland, Tromsö, Norway, and some points in the U.S.S.R. The Bell System began the registration of earth-current disturbances near New York, New York, in 1927. Later this work was somewhat extended and was directed more especially toward securing data on the normal earth-potential effects for use in connection with the International Polar Year.]

[855] Bachmetjew, P. Der gegenwärtige Stand der Frage über elektrische Erdströme. St. Petersburg, Mém. Acad. Sci., **12,** 58 pp. with 6 pls. (1901). [Survey and bibliography of early works.]

[856] Banerji, S. K. Registration of the earth-current with neutral electrodes. Delhi, Mem. India Met. Dept., **26,** pt. 1, 11 pp. with 4 pls. (1933).

[857] Bauer, L. A. Some results of recent earth-current observations and relations with solar activity, terrestrial magnetism, and atmospheric electricity. Terr. Mag., **27,** 1–30 (1922).

[858] Bemis, I. S. Some observations of the behavior of earth-currents and their correlation with magnetic disturbances and radio transmission. Proc. Inst. Radio Eng., **19,** 1931–1947 (1931).

[859] Bemmelen, W. van. Registration of earth-currents at Batavia. Amsterdam, Proc. K. Akad. Wet., **10,** 512–533, 782–789; **11,** 242–248 (1908).

[860] Blavier, E. E. Étude des courants telluriques. Paris, Gauthier-Villars, 30 pp. with 71 curves (1884).

[861] Bosler, J. Les courants telluriques. Traité d'Électricité Atmosphérique et Tellurique, publié sous la direction de E. Mathias. Pp. 453–498 (1924).

[862] Brunhes, B. Sur les courants telluriques. Paris, C.-R. Acad. sci., **151,** 409–411 (1910). [See also *ibid.*, **147,** 1445–1446 (1908); **149,** 74–76 (1909).]

[863] Burbank, J. E. Earth-currents, and a proposed method for their investigation. Terr. Mag., **10,** 23–49 (1905). [Excellent survey of subject to date of publication with a very full bibliography of important papers.]

[864] Chapman, S., and T. T. Whitehead. The influence of electrically conducting material within the Earth on various phenomena of terrestrial magnetism. Cambridge, Trans. Phil. Soc., **22,** 463–482 (1922). [See also Terr. Mag., **28,** 125–128 (1923).]

[865] Chree, C. Earth currents. Encyclopaedia Britannica, 11th ed., **8,** 813–816 (1910). [See also 14th ed., **7,** 837–841 (1929).]

[866] Currie, B. W. Earth-current observations at Chesterfield, Canada. Terr. Mag., **40,** 317–324 (1935).

[867] Egedal, J. On the lunar-diurnal variation in the earth-currents. Terr. Mag., **42,** 179–181 (1937). [See also Zs. Geophysik, **6,** 157–158 (1930).]

[868] Ertel, H. Zum gegenwärtigen Stand der Theorie der durch magnetische Variationen induzierten Erdströme. Naturw., **20,** 860–862 (1932). [See also, Berlin, Veröff. Met. Inst., No. 387, 105–109 (1932).]

[869] Ertel, H. Theorie der durch Variationen des magnetischen Potentials induzierten Erdströme bei ungleichförmiger Leitfähigkeit der Erdrinde. Berlin, Veröff. Met. Inst., No. 391 (Abh. **10,** No. 2), 17 pp. (1932). [Arkiv. Erdmag., Heft 8.]

[870] Forbush, S. E. Apparent vertical earth-current variations at the Huancayo Magnetic Observatory. Terr. Mag., **38,** 1–11 (1933).

[871] Gish, O. H. General description of the earth-current measuring system at the Watheroo Magnetic Observatory. Terr. Mag., **28,** 89–108 (1923).

[872] Gish, O. H. The natural electric currents in the Earth's crust. Sci. Mon., **32,** 5–21 (1931). [See also C.-R. Cong. Internat. Electr., Paris, **12,** 89–109 (1932).]

[873] Gish, O. H. Electrical messages from the Earth; their reception and interpretation. J. Wash. Acad. Sci., **26,** 267–289 (1936); Sci. Mon., **43,** 47–57 (1936).

[874] Gish, O. H. Report on uniform convention regarding the sense of earth-current components. Trans. Edinburgh Meeting 1936; Internat. Union Géod. Géophys., Ass. Terr. Mag. Electr., Bull. No. 10, 235–236 (1937). [Committee report.]

[875] Gish, O. H., and W. J. Rooney. Measurement of resistivity of large masses of undisturbed earth. Terr. Mag., **30,** 161–188 (1925).

[876] Gish, O. H., and W. J. Rooney. On earth-current observations at Watheroo Magnetic Observatory, 1924–1927. Terr. Mag., **33,** 79–90 (1928).

[877] Gish, O. H., and W. J. Rooney. Results of earth-current observations at Huancayo Magnetic Observatory, 1927–1929. Terr. Mag., **35,** 213–224 (1930).

[878] Gish, O. H., and W. J. Rooney. New aspects of earth-current circulations revealed by Polar-Year data. Trans. Edinburgh Meeting 1936; Internat. Union Géod. Géophys., Ass. Terr. Mag. Electr., Bull. No. 10, 378–382 (1937).

[879] Koenigsberger, J., and O. Hecker. Beobachtungen des vertikalen Erdstromes an einem Berge (Gonzen bei Sargans, Schweiz) und in der Ebene (Borth bei Wesel, Niederrhein). Zs. Geophysik, **1**, 152–159 (1925).

[880] Lloyd, H. On earth-currents and their connection with the diurnal changes of the horizontal magnetic needle. Trans. R. Irish Acad., **24**, 115–141 (1862).

[881] Mauchly, S. J. A study of pressure and temperature effects in earth-current measurements. Terr. Mag., **23**, 73–91 (1918).

[882] Nippoldt, A. Über das Wesen des Erdstromes. Met. Zs., **28**, 244–261 (1911).

[883] Oberguggenberger, V. Erdstrombeobachtungen im Gebirge. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **135**, 99–116 (1926). [See also Physik. Zs., **25**, 682–684 (1924).]

[884] Peters, W. J., and C. C. Ennis. The twenty-seven day recurrency in earth-currents. Terr. Mag., **31**, 57–70 (1926).

[885] Rooney, W. J. The significance and accuracy of measurements of earth-current potentials. Terr. Mag., **37**, 363–374 (1932).

[886] Rooney, W. J. Diurnal variation of earth-current potentials on magnetically disturbed and magnetically calm days. Carnegie Inst. Wash., Year Book, No. 31, 270–271 (1932); No. 32, 259 (1933). [See also C.-R. Assemblée Lisbonne 1933; Union Géod. Géophys. Internat., Ass. Mag. Electr. Terr., Bull. No. 9, 248–251 (1934).]

[887] Rooney, W. J. Aurorae and earth-currents. Terr. Mag., **39**, 103–109 (1934). [Comparisons of observations made at College-Fairbanks, Alaska, during International Polar Year 1932–33.]

[888] Rooney, W. J. Seasonal variation in earth-currents at Tucson, Arizona. Terr. Mag., **40**, 183–192 (1935).

[889] Rooney, W. J. Lunar diurnal variation in earth-currents at Huancayo and Tucson. Terr. Mag., **43**, 107–118 (1938).

[890] Rooney, W. J., and O. H. Gish. Results of earth-resistivity surveys near Watheroo, Western Australia, and at Ebro, Spain. Terr. Mag., **32**, 49–63 (1927); **33**, 79–90 (1928).

[891] Rooney, W. J., and O. H. Gish. Earth-resistivity survey at Huancayo, Peru. Terr. Mag., **35**, 61–72 (1930).

[892] Rooney, W. J., and K. L. Sherman. Earth-current measurements at the College-Fairbanks Polar-Year Station. Terr. Mag., **39**, 187–199 (1934).

[893] Southworth, G. C. Earth-potential measurements made during the International Polar Year. Terr. Mag., **40**, 237–254 (1935). [Results of work done by the Bell System at about a dozen different points, mostly in eastern United States. See also Proc. Inst. Radio Eng., **21**, 1740–1748 (1933).]

[894] Stenquist, D. Dependence of the normal earth-current on latitude. Terr. Mag., **36**, 105–109 (1931). [One of the author's latest works; the foot-notes contain references to several of his other papers.]

[895] Venske, O. Die Bedeutung von Erdstrombeobachtungen. Berlin, Veröff. Met. Inst., No. 387, 102–105 (1932).

[896] Weinstein, B. Die Erdströme im deutschen Reichstelegraphengebiet und ihr Zusammenhang mit den erdmagnetischen Erscheinungen. Braunschweig, Vieweg, vi + 78 pp., with atlas of 19 pls. (1900). Review, Terr. Mag., **7**, 149–152 (1902).

[897] Wild, H. Die Beobachtung der elektrischen Ströme der Erde in kürzern Linien. St. Petersbourg, Mém. Acad. Sci., **31**, No. 12, 24 pp. (1883).

(*C*) GEOPHYSICAL PROSPECTING

(*a*) *General*

[898] Alexanian, C. L. Traité pratique de prospection géophysique à l'usage des géologues et des ingénieurs des mines. Paris et Liége, Librairie Polytechnique Ch. Béranger, 268 pp., 133 figs. (1932).

[899] Ambronn, R. Methoden der angewandten Geophysik. Leipzig, Steinkopff, xii + 258 pp. (1926). Translation by Margaret C. Cobb under the title "Elements of geophysics as applied to explorations for minerals, oil, and gas," New York, McGraw-Hill Book Company, Inc., ix + 372 pp. with figs. (1928). [A good review of the methods of geophysical prospecting. Under each subject the elements of pure as well as applied theory are given. Geophysical instruments and their method of use are described and the results of many applied geophysical surveys shown. A comprehensive bibliography of 1,672 articles appended to the text.]

[900] American Institute of Mining and Metallurgical Engineers. Geophysical prospecting. Papers and discussions presented at meetings of the Institute at various times. Thus far three volumes have appeared. They comprise the Transactions of the Society as follows: **81,** 676 pp. (1929); **97,** 510 pp. (1932); **110,** 583 pp. (1934). The papers cover all fields of geophysical prospecting.

[901] Edge, A. B. B., and T. H. Laby. The principles and practice of geophysical prospecting. Being the report of the Imperial Geophysical Experimental Survey. Cambridge, University Press, xiii + 372 pp. with maps (1931). [The object of the Survey was not to prospect for minerals but to test the applicability of various geophysical methods under field conditions in Australia which might be regarded as characteristic of considerable portions of the British Empire.]

[902] Eve, A. S., and D. A. Keys. Geophysical methods of prospecting. A brief and elementary account of the principles involved. Washington, D. C., U. S. Bur. Mines, Tech. Paper 420, 26 pp. (1927).

[903] Eve, A. S., and D. A. Keys. Applied geophysics in the search for minerals. Cambridge, University Press, x + 253 pp. (1929). [The aim is to describe the practical and theoretical sides of the many scientific methods of mining exploration now available and thus to enable engineers and geologists to estimate their relative merits. Magnetic and electric methods are discussed in considerable detail.]

[904] Haalck, H. Lehrbuch der angewandten Geophysik. Berlin, Gebrüder Borntraeger, vii + 376 pp. mit 6 Tafeln (1934). [Practical manual on geophysical prospecting.]

[905] Heiland, C. A. Geophysical methods of prospecting. Principles and recent successes. Q. Colo. School Mines, Golden, Colo., **24,** No. **1,** 163 pp. with 66 figs. (1929). [A very comprehensive report on geophysical methods and operations in North America.]

[906] Heiland, C. A., and D. Wantland. A selected list of books and references on geophysical prospecting. Q. Colo. School Mines, Golden, Colo., **26,** No. 3, 24 pp. (1931). [This list was prepared primarily as a supplement to classroom instruction and contains about 200 items, among which are included those on magnetic and electric methods. Publications in English are listed wherever possible and preference is given to the more recent articles.]

[907] Heiland, C. A., D. Wantland, and R. F. Aldredge. Geophysical studies 1932–1936. Q. Colo. School Mines, Golden, Colo., **32,** 257 pp. (1937).

[908] Hummel, J. N. Unterlagen der geoelektrischen Aufschliessungsmethoden. Beitr. angew. Geophysik, **5**, 32–132 (1935).

[909] Mintrop, L. Zur wirtschaftlichen Bedeutung der geophysikalischen Erforschung von Gebirgsschichten und nutzbaren Lagerstätten. Mitt. Markscheidew., Stuttgart, **48**, 109–132 (1937).

[910] Ottawa, Geological Survey. Studies of geophysical methods 1928 and 1929. Ottawa, Dept. Mines, Geol. Surv., Mem. 165, vi + 227 pp. (1931). [See also similar studies, 1930.]

[911] Reich, H. Angewandte Geophysik für Bergleute und Geologen. Leipzig, Akademische Verlagsgesellschaft, I. Teil, viii + 151 pp. (1933); II. Teil, iv + 153 pp. (1934).

[912] Rothé, E. Les méthodes de prospection du sous-sol. Paris, Gauthier-Villars, viii + 392 pp. (1930).

[913] Siñeriz, J. G. Los métodos geofísicos de prospección y sus aplicaciónes a la resolución de varios problemas geologico-tectónicos. Madrid, Bol. Inst. Geol. Min., **10**, xvi + 505 pp. con 16 laminas (1928).

(*b*) *Magnetic methods*

[914] Haalck, H. Theorie der magnetischen Aufschlussmethoden. Zs. Geophysik, **2**, 1–11, 49–62 (1926).

[915] Haalck, H. Die magnetischen Verfahren der angewandten Geophysik. Berlin, Gebrüder Bornträger, viii + 150 pp., 3 Tafeln (1927).

[916] Haalck, H. Die magnetischen Methoden der angewandten Geophysik. Handbuch der Experimentalphysik, herausgegeben von W. Wien und F. Harms, **25**, III, 305–398. Leipzig, Akademische Verlagsgesellschaft (1930).

[917] Haanel, E. On the location and examination of magnetic ore deposits by magnetometric measurements. Ottawa, Dept. Int., ix + 132 pp., pls. (1904).

[918] Joyce, J. W. Manual on geophysical prospecting with the magnetometer. Washington, D. C., U. S. Dept. Int., Bur. Mines, xi + 129 pp. (1937).

[919] Koenigsberger, J. Zur Deutung der Karten magnetischer Isanomalen und Profile. Beitr. Geophysik, **19**, 241–291 (1928).

[920] Koenigsberger, J. Über den Einfluss von Geländerunebenheiten auf das erdmagnetische Vertikalfeld. Beitr. Geophysik, **20**, 293–307 (1928).

[921] Nippoldt, A. Verwertung magnetischer Messungen zur Mutung für Geologen und Bergingenieure. Berlin, Julius Springer, 74 pp., 36 Tafeln (1930).

(*c*) *Electric methods*

[922] Gish, O. H. Apparatus for the study of the Earth's crust. U. S. Patent, No. 1,813,845, 6 pp. (July 7, 1931).

[923] Graf, A. Theoretische Grundlage der Ringsendemethode. Beitr. angew. Geophysik, **4**, 1–75 (1933).

[924] Haalck, H. Die Verwendung der Elektrizität zur Erforschung des Untergrundes. Beitr. Geophysik, **23**, 99–143 (1929).

[925] Haalck, H., and A. Ebert. Eine elektromagnetische Messungsmethode mit Elektrodenverlegung zur Aufsuchung von Leitfähigkeitsunterschieden im Untergrund. Zs. Geophysik, **8**, 409–419 (1932).

[926] Heine, W. Elektrische Bodenforschung, ihre physikalischen Grundlagen und ihre praktische Anwendung. Berlin, Gebrüder Borntraeger, xi + 222 pp. (1928).

[927] Hummel, J. N., and W. Heine. Die elektrischen Methoden der angewandten Geophysik. Handbuch der Experimentalphysik, herausgegeben von W. Wien

und F. Harms, **25**, III, 399–515. Leipzig, Akademische Verlagsgesellschaft (1930). [Theorie der elektrischen Methoden, von J. N. Hummel; Praktische Anwendung der elektrischen Methoden, von W. Heine.]

[928] Hunkel, H. Die elektrischen Aufschlussmethoden. Handbuch der Geophysik, herausgegeben von B. Gutenberg, **6**, I, 84–165 (1931).

[929] Krahmann, R. Die Anwendbarkeit der geophysikalischer Lagerstättenuntersuchungensverfahren, insbesondere der elektrischen und magnetischen Methoden. Halle (Saale), Verlag von Wilhelm Knapp, 40 pp. (1926).

[930] Lancaster-Jones, E. The earth-resistivity method of electrical prospecting. Min. Mag., **42**, 352–355 (1930); **43**, 19–29 (1930).

[931] Nunier, W. Messung der elektrischen Leitfähigkeit der Erde in verschiedenen Tiefen durch die von einem Kreisstrom induzierten Strome (mit Vermeidung merklichen Skineffekts). Beitr. Geophysik, Ergänzungshefte, **3**, 370–391 (1933).

[932] Rooney, W. J. Earth-resistivity measurements in the Copper Country, Michigan. Terr. Mag., **32**, 97–126 (1927). [See also Amer. Inst. Min. Metall. Eng., Tech. Pub. No. 82, 15 pp. (1928).]

[933] Rooney, W. J. Mesures de la resistivité de la Terre et leur application à la géophysique et aux problèmes techniques. C.-R. Cong. Internat. Electr., Paris, 1932, **12**, 275–290 (1932).

[934] Schlumberger, C. Étude sur la prospection électrique du sous-sol. Paris, Gauthier-Villars, ix + 94 pp. (1920).

[935] Sundberg, K. Prospecting by the Swedish geoelectrical methods. London, Trans. Inst. Min. Metall., **38**, 335–354 (1929).

[936] Tagg, G. F. Practical investigations of earth-resistivity method of geophysical prospecting. Proc. Phys. Soc., **43**, 305–323 (1931).

[937] Whitehead, S., and W. G. Radley. Experiments relating to the distribution of alternating electric currents in the Earth and the measurement of the resistivity of the Earth. Proc. Phys. Soc., **47**, 589–614 (1935).

(*D*) IONOSPHERE

The investigations of the ionosphere may be regarded as dating from the first transmission of radio signals across the Atlantic by Marconi (December 12, 1901) when attempts were made by various investigators to explain, by some sort of diffraction-theory, how radio waves followed the curvature of the Earth. Although it had been suggested by Balfour Stewart about 1882 that daily fluctuations in the Earth's magnetism must depend on the electrical conditions of the Earth's upper atmosphere, and Schuster had shown (1899) by a mathematical analysis that certain variations of the Earth's magnetic field must originate in a region exterior to the Earth's crust, these conclusions were not generally known to engineers. In 1902, A. E. Kennelly and O. Heaviside proposed independently that an electrically conducting layer must exist in the upper atmosphere which reflected the waves back to the Earth. The development of apparatus for the investigation of this conducting region—the ionosphere—the theoretical considerations based on the results obtained, and correlations with terrestrial and cosmical phenomena constitute recent ionospheric research. Reference to some of the chief contributions to the subject are given below.

[938] Appleton, E. V. Geophysical influences on the transmission of wireless waves. Proc. Phys. Soc., **37**, 16*D*–22*D* (1925). [Author's first paper on magneto-ionic theory.]

[939] Appleton, E. V. The existence of more than one ionised layer in the upper atmosphere. Nature, **120**, 330 (1927).

[940] Appleton, E. V. The influence of the Earth's magnetic field on wireless transmission (summary). Union Internat. Radiotél. Sci., Mém. Sci., **1,** 2–3 (1928). [Papers of General Assembly held in Washington, October, 1927. Statement of magneto-ionic theory more fully developed in J. Inst. Elec. Eng., **71,** 642–650 (1932).]

[941] Appleton, E. V. Some notes on wireless methods of investigating the electrical structure of the upper atmosphere (I). Proc. Phys. Soc., **41,** 43–59 (1928).

[942] Appleton, E. V. On some measurements of the equivalent height of the atmospheric ionised layer. Proc. R. Soc., A, **126,** 542–569 (1930).

[943] Appleton, E. V. Some notes on wireless methods of investigating the electrical structure of the upper atmosphere (II). Proc. Phys. Soc., **42,** 321–339 (1930).

[944] Appleton, E. V. Polarisation of downcoming wireless waves in the southern hemisphere. Nature, **128,** 1037 (1931).

[945] Appleton, E. V. Wireless studies of the ionosphere. J. Inst. Elec. Eng., **71,** 642–650 (1932).

[946] Appleton, E. V. On two methods of ionospheric investigation. Proc. Phys. Soc., **45,** 673–688 (1933).

[947] Appleton, E. V. Radio exploration of the ionosphere. Nature, **133,** 793 (1934).

[948] Appleton, E. V. Radio exploration of upper-atmospheric ionization. Phys. Soc., Reports on Progress in Physics, **2,** 129–165 (1936).

[949] Appleton, E. V. Regularities and irregularities in the ionosphere—I. Proc. R. Soc., A, **162,** 451–479 (1937).

[950] Appleton, E. V., and M. A. F. Barnett. On some direct evidence for downward atmospheric reflection of electric waves. Proc. R. Soc., A, **109,** 621–641 (1925).

[951] Appleton, E. V., and M. A. F. Barnett. On wireless interference phenomena between ground waves and waves deviated by the upper atmosphere. Proc. R. Soc., A, **113,** 450–458 (1926).

[952] Appleton, E. V., and G. Builder. The ionosphere as a doubly-refracting medium. Proc. Phys. Soc., **45,** 208–220 (1933).

[953] Appleton, E. V., and F. W. Chapman. The collisional friction experienced by vibrating electrons in ionized air. Proc. Phys. Soc., **44,** 246–254 (1932).

[954] Appleton, E. V., and F. W. Chapman. On the nature of atmospherics—IV. Proc. R. Soc., A, **158,** 1–22 (1937).

[955] Appleton, E. V., and S. Chapman. Report on ionization changes during a solar eclipse. Proc. Inst. Radio Eng., **23,** 658–669 (1935).

[956] Appleton, E. V., and A. L. Green. On some short-wave equivalent height measurements of the ionized regions of the upper atmosphere. Proc. R. Soc., A, **128,** 159–178 (1930).

[957] Appleton, E. V., and R. Naismith. Some measurements of upper-atmospheric ionization. Proc. R. Soc., A, **137,** 36–54 (1932); **150,** 685–708 (1935). [See also Proc. Phys. Soc., **45,** 389–398 (1933).]

[958] Appleton, E. V., and R. Naismith. Some further measurements of upper atmospheric ionization. Proc. R. Soc., A, **150,** 685–708 (1935).

[959] Appleton, E. V., R. Naismith, and G. Builder. Ionospheric investigations in high latitudes. Nature, **132,** 340–341 (1933).

[960] Appleton, E. V., R. Naismith, and L. J. Ingram. British radio observations during the Second International Polar Year 1932–33. Phil. Trans. R. Soc., A, **236,** 191–259 (1937).

[961] Appleton, E. V., and others. Meeting for discussion on the ionosphere. Proc. R. Soc., A, **141,** 697–722 (1933). [E. V. Appleton, S. Chapman, C. T. R. Wilson,

T. L. Eckersley, R. A. Watson Watt, R. A. Ratcliffe, and F. A. Lindemann participated in the discussion.]

[962] Appleton, E. V., and J. H. Piddington. The reflexion coefficients of ionospheric regions. Proc. R. Soc., A, **164,** 467–476 (1938).

[963] Appleton, E. V., and J. A. Ratcliffe. On the nature of wireless signal variations—I. Proc. R. Soc., A, **115,** 291–317 (1927).

[964] Appleton, E. V., and J. A. Ratcliffe. On a method of determining the state of polarisation of downcoming wireless waves. Proc. R. Soc., A, **117,** 576–588 (1928).

[965] Appleton, E. V., and J. A. Ratcliffe. Some simultaneous observations on downcoming wireless waves. Proc. R. Soc., A, **128,** 133–158 (1930).

[966] Appleton, E. V., R. A. Watson Watt, and J. F. Herd. On the nature of atmospherics—II. Proc. R. Soc., A, **111,** 615–677 (1926). [Previous paper, *ibid.*, **103,** 84–102 (1923).]

[967] Austin, L. W. Tables of North Atlantic radio transmission conditions for long-wave daylight signals for the years 1922–1930. Proc. Inst. Radio Eng., **20,** 689–698 (1932). [After the death of Doctor Austin this investigation was completed by E. B. Judson, *ibid.*, **21,** 1354–1363 (1933).]

[968] Bailey, V. A. Study of the magneto-ionic theory of wave-propagation by means of conformal representation. Phil. Mag., **18,** 516–523 (1934).

[969] Bailey, V. A. On some effects caused in the ionosphere by electric waves. Part I. Phil. Mag., **23,** 929–960 (1937). Part II, *ibid.*, **26,** 425–453 (1938).

[970] Bailey, V. A., and D. F. Martyn. The influence of electric waves on the ionosphere. Phil. Mag., **18,** 369–386 (1934).

[971] Baker, W. G., and A. L. Green. The limiting polarization of downcoming radio waves traveling obliquely to the Earth's magnetic field. Proc. Inst. Radio Eng., **21,** 1103–1131 (1933).

[972] Bartels, J. Terrestrial-magnetic activity and its relations to solar phenomena. Terr. Mag., **37,** 1–52 (1932). [See also *ibid.*, **37,** 291–302 (1932); **40,** 1–60 (1935).] [Author outlines important methods for statistical study of physical problems associated with the outer atmosphere.]

[973] Bartels, J. Solar eruptions and their ionospheric effects—a classical observation and its new interpretation. Terr. Mag., **42,** 235–239 (1937). [Review of earlier evidence extending back to 1859.]

[974] Berkner, L. V. The relation of the Pacific eclipse of June 8, 1937, to investigations of changes of ionization of the ionosphere. Terr. Mag., **39,** 317–319 (1934).

[975] Berkner, L. V. The electrical state of the Earth's outer atmosphere. Sci. Mon., **45,** 126–141 (1937). [Popular lecture.]

[976] Berkner, L. V., and H. W. Wells. Report of ionosphere investigations at the Huancayo Magnetic Observatory (Peru) during 1933. Proc. Inst. Radio Eng., **22,** 1102–1123 (1934).

[977] Berkner, L. V., and H. W. Wells. *F*-region ionosphere-investigations at low latitudes. Terr. Mag., **39,** 215–230 (1934).

[978] Berkner, L. V., and H. W. Wells. Abnormal ionization of the *E*-region of the ionosphere. Terr. Mag., **42,** 73–76 (1937).

[979] Berkner, L. V., and H. W. Wells. Study of radio fade-outs. Terr. Mag., **42,** 183–194, 301–309 (1937).

[980] Berkner, L. V., and H. W. Wells. Non-seasonal change of F_2-region ion-density. Terr. Mag., **43,** 15–36 (1938).

[981] Berkner, L. V., H. W. Wells, and S. L. Seaton. Characteristics of the upper region of the ionosphere. Terr. Mag., **41,** 173–184 (1936).

[982] Berkner, L. V., H. W. Wells, and S. L. Seaton. Automatic multifrequency technique for ionospheric measurements. Trans. Edinburgh Meeting, 1936; Internat. Union Géod. Géophys., Ass. Terr. Mag. Electr. Bull. No. 10, 340–357 (1937).

[983] Best, J. E., F. T. Farmer, and J. A. Ratcliffe. Studies of region *E* of the ionosphere. Proc. R. Soc., A, **164**, 96–116 (1938).

[984] Best, J. E., and J. A. Ratcliffe. The diurnal variation of the ionospheric absorption of wireless waves. Proc. Phys. Soc., **50**, 233–246 (1938).

[985] Best, J. E., J. A. Ratcliffe, and M. V. Wilkes. Experimental investigations of very long waves reflected from the ionosphere. Proc. R. Soc., A, **156**, 614–633 (1936).

[986] Bontch-Bruewitch, M. A. Measurements of electrical state of upper stratosphere in polar regions (Kennelly-Heaviside layer). Proc. Inst. Radio Eng., **22**, 1124-1138 (1934).

[987] Booker, H. G. Some general properties of the formulae of the magneto-ionic theory. Proc. R. Soc., A, **147**, 352–382 (1934).

[988] Booker, H. G. The application of the magneto-ionic theory to the ionosphere. Proc. R. Soc., A, **150**, 267–286 (1935).

[989] Booker, H. G. Oblique propagation of electromagnetic waves in a slowly-varying non-isotropic medium. Proc. R. Soc., A, **155**, 235–257 (1936).

[990] Booker, H. G., and L. V. Berkner. Constitution of the ionosphere and the Lorentz polarization correction. Nature, **141**, 562–563 (1938).

[991] Breit, G. A suggestion of a connection between radio fading and small fluctuations in the Earth's magnetic field. Washington, D. C., Bull. Nation. Res. Council, No. 61, 150–158 (1927). With appendix in Proc. Inst. Radio Eng., **15**, 709–723 (1927).

[992] Breit, G., and M. A. Tuve. A test of the existence of the conducting layer. Phys. Rev., **28**, 554–575 (1926). [Also, Nature, **116**, 357 (1925).]

[993] Bureau, R. Abnormalities of the ionosphere and bright solar eruptions. Nature, **139**, 110–111 (1937).

[994] Cairns, J. E. I. Atmospherics at Watheroo, Western Australia. Proc. Inst. Radio Eng., **15**, 985–997 (1927).

[995] Chapman, S. The evidence of terrestrial magnetism for the existence of highly ionized regions in the upper atmosphere. Proc. Phys. Soc., **37**, 38*D*–45*D* (1925).

[996] Chapman, S. Ionization in the upper atmosphere. Q. J. R. Met. Soc., **52**, 225–236 (1926).

[997] Chapman, S. On the diamagnetic field of the outer atmosphere. Terr. Mag., **34**, 1–16 (1929).

[998] Chapman, S. Some phenomena of the upper atmosphere. Proc. R. Soc., A, **132**, 353–374 (1931).

[999] Chapman, S. The absorption and dissociative or ionizing effect of monochromatic radiation in an atmosphere on a rotating earth. Proc. Phys. Soc., **43**, 26–45, 483–501 (1931). [Outline of comprehensive theory of formation of ionospheric regions.]

[1000] Chapman, S. Radio fade-outs and the associated magnetic variations. Terr. Mag., **42**, 417–419 (1937).

[1001] Chapman, S., and E. A. Milne. The composition, ionization, and viscosity of the atmosphere at great heights. Q. J. R. Met. Soc., **46**, 357–398 (1920).

[1002] Colwell, R. C., and A. W. Friend. Tropospheric radio wave reflections. Science, **86**, 473–474 (1937). [See also Nature, **137**, 782 (1936).]

[1003] Darwin, C. G. The refractive index of an ionized medium. Proc. R. Soc., A, **146**, 17–46 (1934). [See also L. Tonks, Nature, **132**, 710–711 (1933).]

[1004] Dellinger, J. H. Sudden ionospheric disturbances. Terr. Mag., **42**, 49–53 (1937). [See also Science, **82**, 351 (1935); Phys. Rev., **48**, 705 (1935), **50**, 1189 (1936); Bur. Stan. J. Res., **19**, 111–141 (1937); Proc. Inst. Radio Eng., **25**, 1253–1290 (1937); J. Applied Phys., **8**, 732–751 (1937).]

[1005] Eccles, W. H. On the diurnal variations of the electric waves occurring in Nature and on the propagation of electric waves round the bend of the Earth. Proc. R. Soc., A, **87**, 79–99 (1912).

[1006] Eckersley, T. L. Studies in radio transmission. J. Inst. Elec. Eng., **71**, 405–454 (1932).

[1007] Eckersley, T. L. Radio transmission problems treated by phase integral methods. Proc. R. Soc., A, **136**, 499–527 (1932).

[1008] Epstein, P. S. Reflection of waves in an inhomogeneous absorbing medium. Proc. Nation. Acad. Sci., **16**, 627–637 (1930).

[1009] Farmer, F. T., and J. A. Ratcliffe. Measurements of the absorption of wireless waves in the ionosphere. Proc. R. Soc., A, **151**, 370–383 (1935).

[1010] Farmer, F. T., and J. A. Ratcliffe. Wireless waves reflected from the ionosphere at oblique incidence. Proc. Phys. Soc., **48**, 839–849 (1936).

[1011] Fleming, J. A. Report of ionosphere-investigations conducted at College-Fairbanks, Alaska, during the winter of 1933–1934. Terr. Mag., **39**, 305–313 (1934).

[1012] Fleming, J. A. Notes on radio fade-out of August 25, 1936. Terr. Mag., **41**, 404–406 (1936).

[1013] Försterling, K., and H. Lassen. Die Ionisation der Atmosphäre und die Ausbreitung der kurzen elektrischen Wellen (10 bis 100 m) über die Erde. Zs. Tech. Physik, **12**, 453–469, 502–527 (1931).

[1014] Försterling, K., and H. Lassen. Kurzwellenausbreitung in der Atmosphäre. Hochfrequenztechnik, **42**, 158–178 (1933).

[1015] Fuchs, J. Eine Radio-Methode zur Bestimmung der Absoluttemperatur der Ionosphäre. Met. Zs., **53**, 41–44 (1936).

[1016] Gilliland, T. R. Ionospheric investigations. Nature, **134**, 379 (1934). [This note contains the basic idea of interlocking radio transmitter and receiver in modern multifrequency ionospheric apparatus.]

[1017] Gilliland, T. R. Multifrequency ionosphere recording and its significance. Bur. Stan. J. Res., **14**, 283–303 (1935); Proc. Inst. Radio Eng., **23**, 1076–1101 (1935).

[1018] Gilliland, T. R., G. W. Kenrick, and K. A. Norton. Investigations of Kennelly-Heaviside layer heights for frequencies between 1600 and 8650 kilocycles per second. Proc. Inst. Radio Eng., **20**, 286–309 (1932).

[1019] Gilliland, T. R., S. S. Kirby, N. Smith, and S. E. Reymer. Averages of critical frequencies and virtual heights of the ionosphere, observed by the National Bureau of Standards, Washington, D. C., 1934–1936. Terr. Mag., **41**, 379–388 (1936). [These values are kept current in issues of this Journal.]

[1020] Goldstein, S. The influence of the Earth's magnetic field on electric transmission in the upper atmosphere. Proc. R. Soc., **121**, 260–285 (1928).

[1021] Goubau, G. Zusammenhang zwischen scheinbarer und wahrer Höhe der Ionosphäre unter Berücksichtigung der magnetischen Doppelbrechung. Hochfrequenztechnik, **44**, 17–23 (1934).

[1022] Goubau, G. Dispersion in einem Elektronen-Ionen-Gemisch, das unter dem Einfluss eines äusseren Magnetfeldes steht. Hochfrequenztechnik, **46**, 37–49 (1935).

[1023] Goubau, G. Zur Dispersionstheorie der Ionosphäre. Hochfrequenztechnik, **45**, 179–185 (1935).

[1024] Gunn, R. The diamagnetic layer of the Earth's atmosphere and its relation to the diurnal variation of terrestrial magnetism. Phys. Rev., **32,** 133–141 (1928). [See also Terr. Mag., **34,** 17–21 (1929).]

[1025] Hallborg, H. E. Terrestrial magnetism and its relation to world-wide short-wave communications. Proc. Inst. Radio Eng., **24,** 455–471 (1936).

[1026] Halliday, E. C. The accurate determination of ionospheric equivalent heights. Proc. Phys. Soc., **48,** 421–432 (1936).

[1027] Handel, P. von, and H. Plendl. Selektive Schwunderscheinungen und Höhenmessungen der Ionosphäre. Elektr. Nachr.-Technik, **10,** 76–94 (1933).

[1028] Hafstad, L. R., and M. A. Tuve. Note on Kennelly-Heaviside layer observations during a magnetic storm. Terr. Mag., **34,** 39–44 (1929).

[1029] Harang, L. Änderungen der Ionisation der höchsten Atmosphärenschichten während der Nordlichter und erdmagnetischer Störungen. Beitr. Geophys., **46,** 438–454 (1936).

[1030] Harang, L. Vertical movements of the air in the upper atmosphere. Terr. Mag., **41,** 143–160 (1936); **42,** 55–72 (1937). [See also *ibid.,* **43,** 41–43 (1938).]

[1031] Hartree, D. R. The propagation of electromagnetic waves in a stratified medium. Cambridge, Proc. Phil. Soc., **25,** 97–120 (1929).

[1032] Hartree, D. R. Optical and equivalent paths in a stratified medium, treated from a wave standpoint. Proc. R. Soc., A, **131,** 428–450 (1931).

[1033] Hartree, D. R. The propagation of electromagnetic waves in a refracting medium in a magnetic field. Cambridge, Proc. Phil. Soc., **27,** 143–162 (1931).

[1034] Heaviside, O. Telegraphy. I. Theory. Encyclopaedia Britannica, 10th ed., **33,** 213–218 (1902). [On p. 215, Heaviside proposes an electrically conducting outer atmosphere to account for bending of radio waves around the Earth.]

[1035] Hollingworth, J. The propagation of radio waves. J. Inst. Elec. Eng., **64,** 579–595 (1926).

[1036] Hollingworth, J. The polarisation of radio waves. Proc. R. Soc., A, **119,** 444–464 (1928).

[1037] Hollingworth, J. The structure of the ionosphere. Proc. Phys. Soc., **47,** 843–851 (1935).

[1038] Hulburt, E. O. Ionization in the upper atmosphere of the Earth. Phys. Rev., **31,** 1018–1037 (1928). [Solar ultraviolet light considered as a cause of the Kennelly-Heaviside layer.]

[1039] Hulburt, E. O. Ions and electrical currents in the upper atmosphere of the Earth. Phys. Rev., **34,** 1167–1183 (1929).

[1040] Hulburt, E. O. Ionization in the upper atmosphere; variation with longitude. Phys. Rev., **35,** 240–247 (1930).

[1041] Hulburt, E. O. Tables of the ionization in the upper atmosphere. Phys. Rev., **39,** 977–992 (1932). [See also *ibid.,* **31,** 1018–1037 (1928); **34,** 1167–1183 (1929); **35,** 240–247 (1930); **53,** 344–351 (1938).]

[1042] Hulburt, E. O. The ionosphere, skip distances of radio waves, and the propagation of microwaves. Proc. Inst. Radio Eng., **23,** 1492–1506 (1935).

[1043] Hulburt, E. O. Theory of the ionosphere. Terr. Mag., **40,** 193–200 (1935).

[1044] Hulburt, E. O. Terrestrial magnetic variations and aurorae. Rev. Modern Phys., **9,** 44–68 (1937). [Deals principally with ionospheric effects.]

[1045] Judson, E. B. Comparison of data on the ionosphere, sunspots, and terrestrial magnetism. Proc. Inst. Radio Eng., **25,** 38–46 (1937).

[1046] Kaplan, J. The excitation of the aurora green line in active nitrogen. Phys. Rev., **33,** 154–156 (1929).

[1047] Kennelly, A. E. On the elevation of the electrically conducting strata of the Earth's atmosphere. Elec. World. Eng., **39**, 473 (March 15, 1902). [This was the first proposal that radio waves were reflected by an electrically conducting outer atmosphere.]

[1048] Kenrick, G. W., and C. K. Jen. Measurements of the height of the Kennelly-Heaviside layer. Proc. Inst. Radio Eng., **17**, 711–733 (1929).

[1049] Kimpara, A. Correlation of atmospherics with thunderstorms. Rep. Radio Res. Japan, **1**, 127–150 (1931).

[1050] Kirby, S. S., L. V. Berkner, T. R. Gilliland, and K. A. Norton. Radio observations of the Bureau of Standards during the solar eclipse of August 31, 1932. Bur. Stan. J. Res., **11**, 829–845 (1933); Proc. Inst. Radio Eng., **22**, 247–264 (1934).

[1051] Kirby, S. S., L. V. Berkner, and D. M. Stuart. Studies of the ionosphere and their application to radio transmission. Proc. Inst. Radio Eng., **22**, 481–521 (1934); Bur. Stan. J. Res., **12**, 15–51 (1934).

[1052] Kirby, S. S., T. R. Gilliland, and E. B. Judson. Ionosphere studies during partial solar eclipse of February 3, 1935. Phys. Rev., **47**, 632–633 (1935); Bur. Stan. J. Res., **16**, 213-225 (1936); Proc. Inst. Radio Eng., **24**, 1027–1040 (1936).

[1053] Kirby, S. S., T. R. Gilliland, N. Smith, and S. E. Reymer. The ionosphere, solar eclipse, and magnetic storm. Phys. Rev., **50**, 258–259 (1936).

[1054] Kirby, S. S., and E. B. Judson. Recent studies of the ionosphere. Bur. Stan. J. Res., **14**, 469–486 (1935); Proc. Inst. Radio Eng., **23**, 733–751 (1935).

[1055] Larmor, J. Why wireless electric rays can bend around the Earth. Phil. Mag., **48**, 1025–1036 (1924). [In this paper the author shows predominant effect of electrons on wave-propagation.]

[1056] Lassen, H. Über die Ionisation der Atmosphäre und ihren Einfluss auf die Ausbreitung der kurzen elektrischen Wellen der drahtlosen Telegraphie. Jahrb. drahtl., Telegr., **28**, 109–113, 139–147 (1926).

[1057] Lorentz, H. A. The theory of electrons and its applications to the phenomena of light and radiant heat. Leipzig, B. G. Teubner, 332 pp. (1909). [The basic theory underlying wave-propagation in the ionosphere is developed in this classical treatment of the electron, originally presented in a series of lectures at Columbia University in 1906.]

[1058] Maris, H. B. The upper atmosphere. Terr. Mag., **33**, 233–255 (1928); **34**, 45–53 (1929).

[1059] McNish, A. G. Terrestrial-magnetic and ionospheric effects associated with bright chromospheric eruptions. Terr. Mag., **42**, 109–122 (1937).

[1060] McNish, A. G. Terrestrial-magnetic variations and the ionosphere. J. Applied Phys., **8**, 718–731 (1937).

[1061] Martyn, D. F. Dispersion and absorption curves for radio-wave propagation in the ionosphere according to the magneto-ionic theory. Phil. Mag., **19**, 376–388 (1935).

[1062] Martyn, D. F. The propagation of medium radio waves in the ionosphere. Proc. Phys. Soc., **47**, 323–339 (1935).

[1063] Martyn, D. F., R. O. Cherry, and A. L. Green. Long-distance observations of radio waves of medium frequencies. Proc. Phys. Soc., **47**, 340–351 (1935).

[1064] Martyn, D. F., and A. L. Green. The characteristics of downcoming radio waves. Proc. R. Soc., A, **148**, 104–120 (1935).

[1065] Martyn, D. F., J. H. Piddington, and G. H. Munro. The polarization of radio echoes. Proc. R. Soc., A, **158**, 536–551 (1937).

[1066] Martyn, D. F., and O. O. Pulley. The temperatures and constituents of the upper atmosphere. Proc. R. Soc., A, **154**, 455–486 (1936).

[1067] Massey, H. S. W. Dissociation, recombination and attachment processes in the upper atmosphere—I. Proc. R. Soc., A, **163**, 542–553 (1937).

[1068] Melbourne, Radio Research Board, Reports. Issued in the series of Bulletins of the Council for Scientific and Industrial Research, Commonwealth of Australia, Report No. 1 being Bull. No. 47 (1931). [These reports contain many valuable contributions to ionospheric research. Report Nos. 5 (1932), 8 (1935), and 10 (1936), being Bull. Nos. 68, 89, and 100, respectively, contain articles pertaining to atmospherics.]

[1069] Millington, G. Ionization charts of the upper atmosphere. Proc. Phys. Soc., **44**, 580–593 (1932); **47**, 263–276 (1935).

[1070] Mimno, H. R. The physics of the ionosphere. Rev. Modern Phys., **9**, 1–43 (1937).

[1071] Mitra, S. K. Report on the present state of our knowledge of the ionosphere. Proc. Nation. Inst. Sci. India, **1**, 131–215 (1935).

[1072] Mögel, H. Über die Beziehungen zwischen Empfangs-Störungen bei Kurzwellen und den Störungen des magnetischen Feldes der Erde. Telefunken-Zeitung, **11**, 14–31 (1930). [See also Zs. Geophysik, **7**, 207–212 (1931).]

[1073] Nambra, S. Polarization phenomena of low-frequency waves. Proc. Inst. Radio Eng., **19**, 1988–2019 (1931).

[1074] Nichols, H. W., and J. C. Schelleng. Propagation of electric waves over the Earth. Bell System Tech. J., **4**, 215–234 (1925).

[1075] Norton, K. A. The propagation of radio waves over the surface of the Earth and in the upper atmosphere. Proc. Inst. Radio Eng., **24**, 1367–1387 (1936); **25**, 1203–1236 (1937).

[1076] Pawsey, J. L. Further investigations of the amplitude variations of downcoming wireless waves. Cambridge, Proc. Phil. Soc., **31**, 125–144 (1935).

[1077] Pedersen, P. O. The propagation of radio waves along the surface of the Earth and in the atmosphere. Copenhagen, Danmarks Naturvidenskabelige Samfund, A. Nr. 15*a*, Appendix, A. Nr. 15*b*, 244 + 15 pp. (1927). [The first complete text on the subject of wave-propagation in the ionosphere.]

[1078] Pedersen, P. O. Wireless echoes of long delay. Proc. Inst. Radio Eng., **17**, 1750–1785 (1929).

[1079] Pekeris, C. L. Atmospheric oscillations. Proc. R. Soc., A, **158**, 650–671 (1937).

[1080] Penndorf, R. Neue Ergebnisse der Ionosphärenforschung und ihre Bedeutung für die Geophysik. Naturw., Berlin, **25**, 774–779 (1937).

[1081] Ratcliffe, J. A. The magneto-ionic theory. Wireless Engineer, **10**, 354–363 (1933).

[1082] Ratcliffe, J. A., and E. L. C. White. The effect of the Earth's magnetic field on the propagation of short wireless waves. Phil. Mag., **16**, 125–144 (1933).

[1083] Ratcliffe, J. A., and J. L. Pawsey. A study of the intensity variations of downcoming wireless waves. Cambridge, Proc. Phil. Soc., **29**, 301–318 (1933).

[1084] Ratcliffe, J. A., and E. L. C. White. An automatic recording method for wireless investigations of the ionosphere. Proc. Phys. Soc., **45**, 399–413 (1933).

[1085] Ratcliffe, J. A., and F. W. G. White. The state of polarization of downcoming wireless waves of medium length. Phil. Mag., **16**, 423–440 (1933).

[1086] Ratcliffe, J. A., and E. L. C. White. Some automatic records of wireless waves reflected from the ionosphere. Proc. Phys. Soc., **46**, 107–115 (1934).

[1087] Richardson, R. S. The bright hydrogen eruption and radio fade-out of April 8, 1936. Terr. Mag., **41**, 197–198 (1936).

[1088] Saha, M. N. The upper atmosphere. Proc. Nation. Inst. Sci. India, **1**, 217–241 (1935).

[1089] Schafer, J. P., and W. M. Goodall. Radio transmission studies of the upper atmosphere. Proc. Inst. Radio Eng., **19**, 1434–1445 (1931).

[1090] Schafer, J. P., and W. M. Goodall. Kennelly-Heaviside layer studies employing a rapid method of virtual-height determination. Proc. Inst. Radio Eng., **20**, 1131–1148 (1932).

[1091] Schafer, J. P., and W. M. Goodall. Some recent studies of the ionization of the ionosphere. Proc. Fifth Pacific Sci. Cong., Canada, 1933, **3**, 2171–2179 (1934).

[1092] Schafer, J. P., and W. M. Goodall. Diurnal and seasonal variations in the ionosphere during the years 1933 and 1934. Proc. Inst. Radio Eng., **23**, 670–682 (1935).

[1093] Schafer, J. P., and W. M. Goodall. Eclipse effects in the ionosphere. Proc. Inst. Radio Eng., **23**, 1356–1360 (1935).

[1094] Schekulin, L. Fortpflanzung einer elektromagnetischen Welle in einem ionisierten magneto-aktiven Medium. Hochfrequenztechnik, **36**, 172–182 (1930).

[1095] Schelleng, J. C. Note on the determination of the ionization in the upper atmosphere. Proc. Inst. Radio Eng., **16**, 1471–1476 (1928).

[1096] Schindelhauer, F. Über elektromagnetische Störungen. Elektr. Nachr.-Technik, **5**, 442–449 (1928); **6**, 231–236 (1929).

[1097] Schindelhauer, F. 27 tägige Periode der "Luftstörungen" der drahtlosen Telegraphie. Naturw., **20**, 672 (1932).

[1098] Schultheiss, F. Die abnormale ionisierung der Ionosphäre. Hochfrequenztechnik, **48**, 7–21 (1936).

[1099] Skellett, A. M. The ionizing effect of meteors in relation to radio propagation. Proc. Inst. Radio Eng., **20**, 1933–1940 (1932).

[1100] Smith-Rose, R. L., and R. H. Barfield. Further measurements on wireless waves received from the upper atmosphere. Proc. R. Soc., A, **116**, 682–693 (1927). [See also Proc. R. Soc., A, **107**, 587–601 (1925) and **110**, 580–614 (1926).]

[1101] Stewart, B. Terrestrial magnetism. Encyclopaedia Britannica, 9th ed., **16**, 159–184 (1878). [The date appearing on the title-page of the volume is obviously in error; internal evidence in the article indicates that the date should be 1882 or 1883. This appears to be Balfour Stewart's first outline of origin of magnetic changes in ionized regions of the outer atmosphere.]

[1102] Störmer, C. Short wave echoes and the Aurora Borealis. Nature, **122**, 681 (1928). [See also Nature, **122**, 878–879 (1928).]

[1103] Swann, W. F. G. On the ionization of the upper atmosphere. Terr. Mag., **21**, 1–8 (1916).

[1104] Taylor, A. H., and E. O. Hulburt. The propagation of radio waves over the Earth. Phys. Rev., **27**, 189–215 (1926).

[1105] Taylor, A. H., and L. C. Young. Studies of high-frequency radio wave propagation. Proc. Inst. Radio Eng., **16**, 561–578 (1928); **17**, 1491–1507 (1929).

[1106] Taylor, M. The Appleton-Hartree formula and dispersion curves for the propagation of electromagnetic waves through an ionized medium in the presence of an external magnetic field. Proc. Phys. Soc., **45**, 245–265 (1933); **46**, 408–435 (1934).

[1107] Tokyo, Radio Research Committee. Reports of radio researches and works in Japan. Compiled by the Radio Research Committee of the National Research Council of Japan. One volume per year. Vol. 1, No. 1, issued June, 1931.

[1108] Tuve, M. A., and O. Dahl. A transmitter modulating device for the study of the Kennelly-Heaviside layer by the echo method. Proc. Inst. Radio Eng., **16**, 794–798 (1928).

[1109] Torreson, O. W., W. E. Scott, and H. E. Stanton. A conspicuous solar eruption on April 8, 1936, and simultaneous disturbances on magnetic, ionospheric, and earth-current records at Huancayo Magnetic Observatory. Terr. Mag., **41**, 199–201 (1936); Science, **83**, 463–464 (1936). [See also Terr. Mag., **41**, 409–410 (1936).]

[1110] Vegard, L. Intensitätsänderungen der grünen und roten Sauerstofflinien und das Auftreten des ϵ-Systems im Nordlicht und Nachthimmellicht. Zs. Physik, **106**, 108–131 (1937).

[1111] Waldmeier, M. Sonneneruptionen und ionosphärische Störungen. Zs. Astroph., **14**, 229–241 (1937).

[1112] Watson Watt, R. A. Weather and wireless. Q. J. R. Met. Soc., **55**, 273–301 (1929).

[1113] Watson Watt, R. A., J. F. Herd, and F. E. Lutkin. On the nature of atmospherics —V. Proc. R. Soc., A, **162**, 267–291 (1937).

[1114] Watson Watt, R. A., A. F. Wilkins, and E. G. Bowen. The return of radio waves from the middle atmosphere—I. Proc. R. Soc., A, **161**, 181–196 (1937). [See also Nature, **137**, 866 (1936).]

[1115] Wells, H. W. Critical frequency observations of the *E*-layer at the Huancayo Magnetic Observatory. Terr. Mag., **39**, 209–214 (1934).

[1116] Wells, H. W., and L. V. Berkner. Polarization of radio waves from the ionosphere near the geomagnetic equator. Terr. Mag., **41**, 75–82 (1936).

[1117] Whatman, A. B., and R. A. Hamilton. High-latitude radio observations. Proc. Phys. Soc., **50**, 217–232 (1938).

[1118] White, F. W. G. The diurnal variation of the intensity of wireless waves reflected from the ionosphere. Proc. Phys. Soc., **46**, 91–106 (1934).

[1119] White, F. W. G. On the automatic registration of the amplitude of downcoming wireless waves—I. Proc. Phys. Soc., **46**, 805–817 (1934).

[1120] White, F. W. G., and L. W. Brown. Some measurements of the reflexion coefficient of the ionosphere for wireless waves. Proc. R. Soc., A, **153**, 639–660 (1936).

(*E*) COSMIC RADIATION

The dates of the beginnings of cosmic-ray research have been the subject of much unprofitable discussion. For our purpose active research in this field may be regarded as dating from about the beginning of the present century, with the works of Elster and Geitel [Physik. Zs., **2**, 116–119, 560–563, 590–593 (1900–1901)] and of C. T. R. Wilson [Cambridge, Proc. Phil. Soc., **11**, 32 (1900); Proc. R. Soc., **68**, 151–161 (1901)]. Wilson showed independently that dry air, contained in a closed vessel, is not a perfect electrical insulator and presents a weak but unquestionable conductivity. It was not, however, until the investigations of Gockel [Physik. Zs., **12**, 595–597 (1911)], Hess [Physik. Zs., **13**, 1084–1091 (1912); **14**, 1066–1069, 1153–1156 (1913)], and others that the intensity of cosmic rays was proved to increase with altitude indicating an extra-terrestrial origin. After the World War, research was renewed with much enthusiasm and is still in progress.

In December, 1932, a Committee on Coordination of Cosmic-Ray Investigations was appointed by the President of the Carnegie Institution of Washington, which has concerned itself with the development of precision meters and their installation at stations suitably distributed over the Earth's surface with a view of obtaining continuous records over considerable periods of time and of analyzing them. Its reports are published in the Year Books of the Carnegie Institution of Washington beginning with No. 32 for the year 1932–33.

The literature on cosmic radiation has expanded to such proportions that it is possible to indicate here only some of the principal surveys of the subject and important papers dealing with special lines of investigation thus far followed. The bibliographies found in most of the general articles will furnish references to those who desire to study the subject in detail.

[1121] Anderson, C. D. Cosmic-ray positive and negative electrons. Phys. Rev., **44**, 406–416 (1933).

[1122] Anderson, C. D., R. A. Millikan, S. Neddermeyer, and W. Pickering. The mechanism of cosmic-ray counter action. Phys. Rev., **45**, 352–363 (1934).

[1123] Anderson, C. D., and S. H. Neddermeyer. Cloud chamber observations of cosmic rays at 4300 meters elevation and near sea-level. Phys. Rev., **50**, 263–271 (1936); **51**, 884–886 (1937).

[1124] Auger, P. Tableau schématique des connaissances actuelles sur les rayons cosmiques. J. Phys. et Le Radium, **5**, 1–5 (1934).

[1125] Auger, P., et L. Leprince-Ringuet. Étude de la variation du rayonnement cosmique entre les latitudes 45° Nord et 38° Sud. C.-R. Acad. sci., **197**, 1242–1244 (1933).

[1126] Bhabha, H. J. On the penetrating component of cosmic radiation. London, Proc. R. Soc., A, **164**, 257–294 (1938).

[1127] Blackett, P. M. S. On the technique of the counter controlled cloud chamber. Proc. R. Soc., A, **146**, 281–299 (1934).

[1128] Blackett, P. M. S. La radiation cosmique. Paris, Hermann et Cie, Éditeurs (1935). [This treatise appeared in the collection "Actualités scientifiques et industrielles" of which it forms Nos. 230 to 233. The subtitles of the four parts are: Aperçu général (22 pp. with 4 pls.); La méthode de la chambre de C. T. R. Wilson (24 pp. with 3 pls.); L'action du champ magnétique terrestre (19 pp. with 1 pl.); La perte d'énergie par ionisation (20 pp. with 7 pls.).]

[1129] Blackett, P. M. S. Cosmic rays. Being the Halley Lecture delivered on 5 June 1935. Oxford, Clarendon Press, 25 pp., 2 pls. (1936).

[1130] Blackett, P. M. S. The nature of the penetrating component of cosmic rays. Proc. R. Soc., A, **165**, 11–31 (1938).

[1131] Blackett, P. M. S., and R. B. Brode. The measurement of the energy of cosmic rays. Proc. R. Soc., A, **154**, 564–587 (1936). [See also *ibid.*, **159**, 1–18 (1937).]

[1132] Blackett, P. M. S., and G. P. S. Occhialini. Some photographs of the tracks of penetrating radiation. Proc. R. Soc., A, **139**, 699–720 (1933).

[1133] Bothe, W., and W. Kolhörster. Das Wesen der Höhenstrahlung. Zs. Physik, **56**, 751–777 (1929). [Experiments with "Geiger counters."]

[1134] Bowen, I. S., R. A. Millikan, and H. V. Neher. New high-altitude study of cosmic-ray bands and a new determination of their total energy content. Phys. Rev., **44**, 246–252 (1933).

[1135] Bowen, I. S., R. A. Millikan, and H. V. Neher. A very high altitude survey of the effect of latitude upon cosmic-ray intensities and an attempt at a general interpretation of cosmic-ray phenomena. Phys. Rev., **46**, 641–652 (1934).

[1136] Bowen, I. S., R. A. Millikan, and H. V. Neher. The influence of the Earth's magnetic field on cosmic-ray intensities up to the top of the atmosphere. Phys. Rev., **52**, 80–88 (1937).

[1137] Büttner, K. Die durchdringende Strahlung. Wien-Harms, Handbuch der Experimentalphysik, **25**, I, 479–523 (1928).

[1138] Clay, J. Penetrating radiation. Amsterdam, Proc. K. Acad. Wet., **30**, 1115–1127 (1927); **31**, 1091–1097 (1928). [Author's first measurements indicating greater cosmic-ray intensity in Holland than in Java.]

[1139] Clay, J., and collaborators. Results of the Dutch Cosmic-Ray Expedition 1933. Physica, **1,** 363–382, 829–848 (1934); **2,** 183–195; 299–308, 861–869 (1935); **3,** 775–796 (1936).

[1140] Compton, A. H. A geographic study of cosmic rays. Sci. Mon., **36,** 75–87 (1933); Phys. Rev., **43,** 387–403 (1933).

[1141] Compton, A. H. An attempt to analyse cosmic rays. Proc. Phys. Soc., **47,** 747–773 (1935).

[1142] Compton, A. H. Recent developments in cosmic rays. Rev. Sci. Instr., **7,** 71–81 (1936). [Preceded by a brief summary of the early history of the subject.]

[1143] Compton, A. H. Cosmic rays as electrical particles. Phys. Rev., **50,** 1119–1130 (1936).

[1144] Compton, A. H., and I. A. Getting. An apparent effect of galactic rotation on the intensity of cosmic rays. Phys. Rev., **47,** 817–821 (1925).

[1145] Compton, A. H., and R. J. Stephenson. Cosmic ray ionization at high altitudes. Phys. Rev., **45,** 441–450 (1934).

[1146] Compton, A. H., E. O. Wollan, and R. D. Bennett. A precision recording cosmic-ray meter. Rev. Sci. Instr., **5,** 415–422 (1934).

[1147] Corlin, A. Cosmic ultra-radiation in northern Sweden. Lund, Ann. Obs., No. 4, 194 pp. (1934). [Academical dissertation. Contains a detailed historical introduction and chapters on cosmic-ray measurements in northern Sweden, meteorological influences on cosmic rays, cosmic rays and earth-magnetic disturbances, intensity of cosmic rays down to 800 meters of water-equivalent, and the origin of cosmic radiation together with 74 pages of tabulated data. There is appended a long list of references—388 items.]

[1148] Curtiss, L. F., A. V. Astin, L. L. Stockmann, B. W. Brown, and S. A. Korff. Cosmic-ray observations in the stratosphere. Phys. Rev., **53,** 23–29 (1938).

[1149] Darrow, K. K. Data and nature of cosmic rays. Bell System Tech. J., **11,** 148–184 (1932).

[1150] Demmelmair, A. Die Schwankungen der kosmischen Strahlung nach Ortzeit und nach Sternzeit auf dem Hafelekar (1936–1937). Wien, SitzBer. Ak. Wiss., Abt. II*a*, **146,** 643–659 (1937).

[1151] Department of Terrestrial Magnetism, Carnegie Institution of Washington. Model C cosmic-ray meter. Washington, D. C., 27 pp. (1935).

[1152] Doan, R. L. Fluctuations in cosmic-ray ionization as given by several recording meters located at the same station. Phys. Rev., **49,** 107–122 (1936).

[1153] Doan, R. L. Apparatus for transmitting cosmic-ray data from the stratosphere. Rev. Sci. Instr., **7,** 400–406 (1936).

[1154] Forbush, S. E. On diurnal variation in cosmic-ray intensity. Terr. Mag., **42,** 1–16 (1937).

[1155] Forbush, S. E. On the effects in cosmic-ray intensity observed during the recent magnetic storm. Phys. Rev., **51,** 1108–1109 (1937). [See also V. F. Hess and A. Demmelmair, Nature, **140,** 316–317 (1937).]

[1156] Gilbert, C. W. The production of showers by cosmic radiation. Proc. R. Soc., **144,** 559–573 (1934).

[1157] Hess, V. F., R. Steinmaurer, and H. Graziadei. Ergebnisse der Registrierung der kosmischen Ultrastrahlung auf dem Hafelekar (2300 m) bei Innsbruck vom 1 September 1931 bis 30 November 1932. Berlin, SitzBer. Ak. Wiss., 521–542; 672–685 (1933).

[1158] Hoffmann, G. Probleme der Ultrastrahlung. Physik. Zs., **33,** 633–662 (1932). [Contains a bibliography covering period 1924–32, 307 titles.]

[1159] Johnson, T. H. Cosmic rays—theory and experimentation. J. Frank. Inst., **214,** 665–689 (1932).

[1160] Johnson, T. H. Coincidence counter studies of the corpuscular component of the cosmic radiation. Phys. Rev., **45,** 569–585 (1934).

[1161] Johnson, T. H. The nature of the cosmic radiation. J. Frank. Inst., **220,** 41–67 (1935). Reprinted in Smithsonian Inst. Rep. for 1935, 197–214 (1936).

[1162] Johnson. T. H. Radio-transmission of coincidence counter cosmic-ray measurements in the stratosphere. J. Frank. Inst., **223,** 339–354 (1937).

[1163] Johnson, T. H., and D. N. Read. Unidirectional measurements of the cosmic-ray latitude effect. Phys. Rev., **51,** 557–564 (1937).

[1164] Kolhörster, W. Die durchdringende Strahlung in der Atmosphäre. Hamburg, Henri Grand, 72 pp. (1924).

[1165] Kolhörster, W., and L. Jánossy. Die Richtungsverteilung koinzidierender Höhenstrahlen in Seehöhe. Zs. Physik, **93,** 111–122 (1935).

[1166] Kolhörster, W., and L. Tuwim. Die Barometereffekt der Höhenstrahlung. Ergebnisse der kosmischen Physik, **1,** 87–126 (1931).

[1167] Kolhörster, W., and L. Tuwim. Absorptionskoeffizienten der Höhenstrahlung. Ergebnisse der kosmischen Physik, **1,** 127–179 (1931).

[1168] Korff, S. A., L. F. Curtiss, and A. V. Astin. The latitude effect in cosmic radiation at high altitudes. Phys. Rev., **53,** 14–22 (1938).

[1169] Kunze, P. Untersuchung der Ultrastrahlung in der Wilsonkammer. Zs. Physik, **83,** 1–18 (1933). [Measurements of energies of trajectories.]

[1170] Lemaître, G., and M. S. Vallarta. On Compton's latitude effect of cosmic radiation. Phys. Rev., **43,** 87–91 (1933).

[1171] Lemaître, G., and M. S. Vallarta. On the geomagnetic analysis of cosmic radiation. Phys. Rev., **49,** 719–726 (1936). [See also, for later paper, Phys. Rev., **50,** 493–504 (1936).]

[1172] Locher, G. L. Wilson cloud machines for portable use. Rev. Sci. Instr., **7,** 471–478 (1936). [Description of two new forms of Wilson cloud-apparatus developed for stratosphere balloon-flights and suitable for portable use.]

[1173] London, Physical Society. A discussion on ionization in the atmosphere and its influence on the propagation of wireless signals. Proc. Phys. Soc., **37,** 1*D*–50*D* (1925).

[1174] Messerschmidt, W. Über Schwankungsmessungen der Ultrastrahlung. Zs. Physik, **78,** 668–689 (1932).

[1175] Messerschmidt, W. Untersuchungen über Ultrastrahlungsstösse. Zs. Physik, **103,** 27–56 (1936).

[1176] Massey, H. S. W. Dissociation, recombination and attachment processes in the upper atmosphere—I. Proc. R. Soc., A, **163,** 542–553 (1937).

[1177] Miehlnickel, E. Höhenstrahlung (Ultrastrahlung). Leipzig, T. Steinkopff, xv + 316 pp., 39 figs. (1938). [An excellent summary of cosmic-ray research up to the end of 1937. It contains a very complete bibliography of the subject consisting of nearly 2,900 items.]

[1178] Millikan, R. A. New techniques in the cosmic-ray field and some of the results obtained with them. Phys. Rev., **43,** 661–669 (1933).

[1179] Millikan, R. A., and I. S. Bowen. High frequency rays of cosmic origin. I. Sounding balloon observations at extreme altitudes. Phys. Rev., **27,** 353–361 (1926).

[1180] Millikan, R. A., and G. H. Cameron. High frequency rays of cosmic origin. III. Measurements in snow-fed lakes at high altitudes. Phys. Rev., **28,** 851–868 (1926).

[1181] Millikan, R. A., and G. H. Cameron. High altitude tests on the geographical, directional, and spectral distribution of cosmic rays. Phys. Rev., **31,** 163–173 (1928).

[1182] Millikan, R. A., and H. V. Neher. The equatorial longitude effect in cosmic rays. Phys. Rev., **47,** 205–208 (1935).

[1183] Millikan, R. A., and H. V. Neher. A precision world survey of sea-level cosmic-ray intensities. Phys. Rev., **50,** 15–24 (1936).

[1184] Millikan, R. A., and R. M. Otis. High frequency rays of cosmic origin. II. Mountain peak and airplane observations. Phys. Rev., **27,** 645–658 (1926).

[1185] Mott-Smith, L. M. An attempt to measure the energy of the cosmic electrons by magnetic deflection. Phys. Rev., **37,** 1001–1003 (1931).

[1186] Mott-Smith, L. M., and G. L. Locher. A new experiment bearing on cosmic-ray phenomena. Phys. Rev., **38,** 1399–1408 (1931). [Simultaneous observations by Wilson cloud expansion apparatus and the Geiger counter method.]

[1187] Nordheim, L. W. A new analysis of cosmic radiation including the hard component. Phys. Rev., **53,** 694–706 (1938).

[1188] Priebsch, J. A., and R. Steinmaurer. Ganzjährige Registrierbeobachtungen der kosmischen Ultrastrahlung auf dem Hohen Sonnblick (3106 m). Beitr. Geophysik, **37,** 296–314 (1932).

[1189] Regener, E. Die Absorptionskurve der Ultrastrahlung und ihre Deutung. Physik. Zs., **34,** 306–323 (1933). [See also Zs. Physik, **74,** 433–454 (1932).] [Reports on measurements in Lake Constance down to 230 meters and in the stratosphere up to 25 km.]

[1190] Regener, E. Die kosmische Ultrastrahlung. Naturw., **25,** 1–11 (1937).

[1191] Regener, E., and G. Pfotzer. Messungen der Ultrastrahlung in der oberen Atmosphäre mit dem Zählrohr. Physik. Zs., **35,** 779–784 (1934).

[1192] Rossi, B. Un metodo per lo studio della deviazione magnetica dei raggi penetranti. Rend. Acc. Lincei, **11,** 478–482 (1930).

[1193] Rossi, B. Über die Eigenschaften der durchdringenden Korpuskularstrahlung im Meeresniveau. Zs. Physik, **82,** 151–178 (1933).

[1194] Rossi, B. Le attuali conoscenze sperimentali sulla radiazione cosmica. Nuovo Cimento, **15,** 43–65 (1938).

[1195] Schonland, B. F. J., B. Delatizky, and J. Gaskell. Intensity-measurements of the cosmic radiation in Capetown during 1933, 1934, and 1935. Terr. Mag., **42,** 137–152 (1937).

[1196] Skobelzyn, D. Über eine neue Art sehr schneller β-Strahlen. Zs. Physik, **54,** 686–702 (1929). [Experiments by expansion-chamber method.]

[1197] Steinke, E. Neue Untersuchungen über die durchdringende Hesssche Strahlung. Zs. Physik, **48,** 647–689 (1928).

[1198] Steinke, E. G. Die kosmische Ultrastrahlung. Ergebnisse der exakten Naturwissenschaften, **13,** 89–147 (1934). [Contains a bibliography of 704 titles covering period 1908–34.]

[1199] Street, J. C., and T. H. Johnson. Concerning the production of groups of secondaries by the cosmic radiation. Phys. Rev., **42,** 142–144 (1932).

[1200] Swann, W. F. G. A numerically consistent corpuscular theory of cosmic rays. Phys. Rev., **50,** 1103–1119 (1936).

[1201] Vallarta, M. S. The interpretation of the azimuthal effect of cosmic radiation. Phys. Rev., **44,** 1–3 (1933).

[1202] Viljoen, J. P. T., and B. F. J. Schonland. The distribution of the ionizing particles of the penetrating radiation in relation to the magnetic meridian. Phil. Mag., **16,** 449–456 (1933).

[1203] Wigand, A. Die durchdringende Höhenstrahlung. Physik. Zs., **25,** 445–463 (1924). [Historisches, Messverfahren, Eigenschaften, Ursprung, Zusammenhang mit Erdfeldproblem, Aufgaben, Literaturverzeichnis (107 papers).]

(*F*) RADIOACTIVITY

[1204] Běhounek, F. Ein Beitrag zu den Versuchen über die Beeinflussung des radioaktiven Zerfalles. Physik. Zs., **31,** 215–224 (1930).

[1205] Bender, H. Über den Gehalt der Bodenlüft an Radiumemanation. Beitr. Geophysik, **41,** 401-415 (1934).

[1206] Blackwood, O. H. A determination of the diurnal variation of the radioactivity of the atmosphere at Manila by the active deposit method. Philippine J. Sci., **10,** 37–47 (1915).

[1207] Bongards, H. Radioaktive Zerfallsprodukte in der Atmosphäre und die Wahrscheinlichkeit ihrer Herkunft von der Sonne. Physik. Zs., **21,** 141–145 (1920); **24,** 16–19, 295–296 (1923).

[1208] Bongards, H. On the cosmic origin of the radioactive substances in the atmosphere. Astroph. J., **58,** 307–313 (1923).

[1209] Dike, P. H. The diurnal variation of the amount of radioactive emanation in the atmosphere. Terr. Mag., **11,** 125–129 (1906).

[1210] Geiger, H., and W. Makower. Messmethoden auf dem Gebiete der Radioaktivität. Braunschweig, Vieweg., ix + 156 pp. (1920).

[1211] Gockel, A. Sur la radioactivité de l'atmosphère. Arch. Sci. Phys., **27,** 248–255 (1909).

[1212] Gockel, A. Die Radioaktivität von Boden und Quellen. Braunschweig, Vieweg, v + 108 pp. (1914).

[1213] Hess, V. F. Über die Verteilung der radioaktiven Substanzen in und über dem Meere. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **127,** 1297–1313 (1918).

[1214] Hewlett, C. W. The radium content of sea-salt specimens collected on cruise IV of the *Carnegie*. Terr. Mag., **22,** 173–181 (1917).

[1215] Hummel, J. N. Radioaktive Methoden. Handbuch der Experimentalphysik, herausgegeben von H. Geiger und K. Scheel, **25,** III, 517–539 (1930).

[1216] Joly, J. The radioactivity of terrestrial surface materials. Phil. Mag., **24,** 694–705 (1912).

[1217] Kohlrausch, K. W. F. Über Radiuminduktion in der atmosphärischen Luft und eine Methode zur absoluten Messung derselben. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **115,** 1263–1268 (1906).

[1218] Kosmath, W. Der Gehalt der Freiluft an Radiumemanation und deren vertikale Verteilung in der Nähe des Erdbodens (nach Beobachtungen in Graz im Jahre 1928). Beitr. Geophysik, **25,** 95–117 (1930).

[1219] Kovarik, A. F., and L. W. McKeehan. Radioactivity. Report of committee on X-rays and radioactivity. Bull. Nation. Res. Council, No. 51, 203 pp. (1925).

[1220] Macek, O. Zur Frage der Sorption von Radon und seiner Folgeprodukte durch Aerosole. Beitr. Geophysik, **47,** 340–356 (1936). [With brief list of references.]

[1221] Mauchly, S. J. The radium-emanation content of sea air from observations aboard the *Carnegie*, 1915–1921. Terr. Mag., **29,** 187–194 (1924).

[1222] Meyer, St., and E. Schweidler. Radioaktivität. Leipzig, B. G. Teubner, 2. Aufl., x + 721 pp. (1927). [Excellent general treatise.]

[1223] Piggot, C. S. Radium-content of ocean-bottom sediments. Trans. Amer. Geophys. Union, 13th Annual Meeting, 233–238 (1932); Amer. J. Sci., **25,** 229–238 (1933).

[1224] Priebsch, J. A. Zur Verteilung radioaktiver Stoffe in der freien Luft. Physik. Zs., **32,** 622–629 (1931). [At end of article are given ten references to previous papers bearing on this subject.]

[1225] Priebsch, J. A. Über die Radioaktivität der atmosphärischen Niederschläge. Beitr. Geophysik, **36,** 304–318 (1932). [Contains bibliography of pertinent literature.]

[1226] Priebsch, J. A., G. Radinger, and P. L. Dymek. Untersuchungen über den Radiumemanationsgehalt der Freiluft in Innsbruck und auf dem Hafelekar (2300 m). Beitr. Geophysik, **50,** 54–77 (1937).

[1227] Salpeter, J. Über den Einfluss des Erdfeldes auf die Verteilung der Radiuminduktion in der Atmosphäre und auf der Erdoberfläche. Wien, SitzBer. Ak. Wiss., Abt. II*a*, **118,** 1163–1171 (1909); **119,** 107–118 (1910).

[1228] Schmid, E. Der Gehalt der Freiluft an Radiumemanation und deren vertikale Verteilung in der Nähe des Erdbodens. (Nach Beobachtungen in St. Peter bei Graz im Jahre 1930.) Wien, SitzBer. Ak. Wiss., Abt. II*a*, **140,** 27–48 (1931).

[1229] Wigand, A., and F. Wenk. Der Gehalt der Luft an Radium-Emanation, nach Messungen bei Flugzeugaufstiegen. Ann. Physik, **86,** 657–686 (1928).

[1230] Zeilinger, P. R. Über die Nachlieferung von Radiumemanation aus dem Erdboden. Terr. Mag., **40,** 281–294 (1935).

[1231] Zupancic, P. R. Messungen der Exhalation von Radiumemanation aus dem Erdboden. Terr. Mag., **39,** 33–46 (1934).

(*G*) Ozone

[1232] Chapman, S. A theory of upper-atmospheric ozone. Mem. R. Met. Soc., **3,** 103–125 (1930). [See also Phil. Mag., **10,** 369–383 (1930).]

[1233] Chapman, S. On ozone and atomic oxygen in the upper atmosphere. Phil. Mag., **10,** 369–383 (1930).

[1234] Chapman, S. Some phenomena of the upper atmosphere. Proc. R. Soc., A, **132,** 353–374 (1931).

[1235] Chapman, S. The Götz inversion of intensity-ratio in zenith-scattered sunlight. Phil. Trans. R. Soc., A, **234,** 205–230 (1935).

[1236] Dobson, G. M. B. Observations of the amount of ozone in the Earth's atmosphere, and its relation to other geophysical conditions. Proc. R. Soc., A, **129,** 411–433 (1930). [See also previous papers, *ibid.*, **110,** 660–693 (1926); **114,** 521–541 (1927); **122,** 456–486 (1929).]

[1237] Fabry, C. The absorption of radiation in the upper atmosphere. Proc. Phys. Soc., **39,** 1–14 (1926).

[1238] Fabry, C., and H. Buisson. L'absorption de l'ultra-violet par l'ozone et la limite du spectre solaire. J. phys., Paris, **3,** 196–206 (1913).

[1239] Fowle, F. E. Further ozone-measures and the possible connection of ozone with the sunspot-cycle. Trans. Amer. Geophys. Union, 15th Annual Meeting, I, 160–162 (1934); 16th Annual Meeting, I, 164–165 (1935).

[1240] Götz, F. W. P. Das atmosphärische Ozon. Leipzig, Ergebnisse der kosmischen Physik, **1,** 180–235 (1931). [Contains an extensive bibliography.]

[1241] Götz, F. W. P., A. R. Meetham, and G. M. B. Dobson. The vertical distribution of ozone in the atmosphere. Proc. R. Soc., A, **145,** 416–446 (1934).

[1242] Hanson, M. P., and E. O. Hulburt. On some solar and lunar spectra taken in Little America, Antarctica. Phys. Rev., **37,** 477–480 (1931).

[1243] Higgs, A. J. Measurements of atmospheric ozone made at the Commonwealth Solar Observatory, Mount Stromlo, Canberra, during the years 1929 to 1932. Mem. Commonwealth Solar Obs., **1,** No. 3, 29 pp. (1934).

[1244] Mecke, R. The photochemical ozone equilibrium in the atmosphere. Trans. Faraday Soc., **27**, 375–377 (1931).

[1245] Mecke, R. Zur Deutung des Ozongehaltes der Atmosphäre. Zs. physik. Chem., Bodenstein-Festband, 392–404 (1931).

[1246] Meetham, A. R. The correlation of the amount of ozone with other characteristics of the atmosphere. Q. J. R. Met. Soc., **63**, 289–305 (1937).

[1247] Meetham, A. R., and G. M. B. Dobson. The vertical distribution of atmospheric ozone in high latitudes. Proc. R. Soc., A, **148**, 598–603 (1935).

[1248] O'Brien, B., F. L. Mohler, and H. S. Stewart. Spectroscopic results of 1935 flight. Nation. Geog. Soc., Contrib. Tech. Papers, Stratosphere Ser., No. 2, 71–93 (1936).

[1249] Penndorf, R. Beiträge zum Ozonproblem. Die Rolle des Ozons im Wärmehaushalt der Stratosphäre. Leipzig, Veröff. Geophys. Inst. Univ., 2. Ser., Spezialarbeiten Geophys. Inst. u. Obs., **8**, No. 4, 181–285 (1936). [Good summary with comprehensive bibliography of 177 items.]

[1250] Regener, E. Erfahrungen und Ergebnisse mit Registrierballonen und Registrierapparaten in der Stratosphäre. Beitr. Physik. frei. Atmos., **22**, 249–260 (1935). [See also Nature, **134**, 380 (1934).]

[1251] Regener, E., and V. H. Regener. Aufnahmen des ultravioletten Sonnenspektrums in der Stratosphäre und vertikale Ozonverteilung. Physik. Zs., **35**, 788–793 (1934).

[1252] Royal Meteorological Society. Conference on atmospheric ozone held at Oxford, September 9–11, 1936. Papers read at the Conference. Q. J. R. Met. Soc., **62**, Sup., iv + 76 pp. (1936).

[1253] Vassy, E. Sur quelques propriétés de l'ozone et leurs conséquences géophysiques. Ann. Phys., Paris, **8**, 679–777 (1937). [Good summary of the subject.]

[1254] Wulf, O. R. A theory of the ozone of the lower atmosphere and its relation to the general problem of atmospheric ozone. Phys. Rev., **41**, 375–376 (1932).

[1255] Wulf, O. R. Steady states produced by radiation with application to the distribution of atmospheric ozone. Phil. Mag., **17**, 251–263 (1934).

[1256] Wulf, O. R. Light absorption in the atmosphere and its photochemistry. J. Optical Soc. Amer., **25**, 231–236 (1935).

[1257] Wulf, O. R., and L. S. Deming. The theoretical calculation of the distribution of photochemically formed ozone in the atmosphere. Terr. Mag., **41**, 299–310, 375–378 (1936); **42**, 195–202 (1937).

(*H*) MISCELLANEOUS

(*A-a to A-j*) *Terrestrial magnetism*

[1258] Barnett, S. J. The magnetization of iron, nickel, and cobalt by rotation and the nature of the magnetic molecule. Phys. Rev., **10**, 7–21 (1917).

[1259] Barnett, S. J. Gyromagnetic effects: History, theory, and experiments. Physica, **13**, 241–268 (1933); Physik. Zs., **35**, 203–205 (1934).

[1260] Bartels, J. Geophysical stereograms. Terr. Mag., **36**, 187–198 (1931).

[1261] Bartels, J. Tides in the atmosphere. Sci. Mon., **35**, 110–130 (1932). [Carnegie Inst. Sup. Pub. No. 5, 48–68 (1932).]

[1262] Bauer, L. A. On vertical electric currents and the relation between terrestrial magnetism and atmospheric electricity. Terr. Mag., **25**, 145–162 (1920).

[1263] Carlheim-Gyllensköld, V. Note sur le potentiel magnétique de la Terre exprimé en fonction du temps. Arkiv. Mat., Astr., Fys., **3**, No. 7 (1906).

[1264] Chapman, S. The lunar diurnal variation of atmospheric temperature at Batavia, 1866–1928. Proc. R. Soc., A, **137**, 1–24 (1932).

[1265] Chapman, S. The lunar tide in the Earth's atmosphere. Proc. R. Soc., A, **151**, 105–117 (1935).

[1266] Gunn, R. Earth-movements and terrestrial-magnetic variations. Terr. Mag., **35**, 151–156 (1930).

[1267] Jeffreys, H. The Earth. Its origin, history, and physical constitution. 2d ed. Cambridge, University Press, ix + 346 pp. (1929).

[1267-*A*] Kashiwagi, Y. Short period magnetographs. Kyoto, Mem. Coll. Sci. Eng., **1**, No. 3, 217–227 (1907).

[1268] Lamb, H. On electrical motions in a spherical conductor. Phil. Trans. R. Soc., **174**, 519–549 (1883).

[1269] Larmor, J. How could a rotating body such as the Sun become a magnet? Rep. Brit. Ass. Adv. Sci., Bournemouth Meeting, 1919, 159–160 (1920).

[1269-*A*] McFarland, W. E. Direct scaling of absolute magnetic values. Terr. Mag., **31**, 89–95 (1926).

[1270] McNish, A. G. The Earth's interior as inferred from terrestrial magnetism. Trans. Amer. Geophys. Union, 18th Annual Meeting, 1937, I, 43–50 (1937).

[1271] McNish, A. G. Heights of electric currents near the auroral zone. Terr. Mag., **43**, 67–75 (1938).

[1272] Maris, H. B., and E. O. Hulburt. The ultra-violet light of the Sun as the origin of aurorae and magnetic storms. Nature, **122**, 807–808 (1928).

[1273] Maris, H. B., and E. O. Hulburt. Comets and terrestrial-magnetic storms. Phys. Rev., **33**, 1046–1060 (1929). [See also Trans. Amer. Geophys. Union, 12th Annual Meeting, 131–132 (1931).]

[1274] Meinesz, F. A. Vening. Gravity and the hypothesis of convection-currents in the Earth. Amsterdam, Proc. Sci. K. Akad. Wet., **37**, 37–45 (1934).

[1275] Peters, W. J. Tilting deviations in magnetic declinations. Terr. Mag., **34**, 93–115 (1929).

[1276] Peters, W. J. Present status of the investigation on dynamic and tilting deviations in the Department of Terrestrial Magnetism, Carnegie Institution of Washington. Terr. Mag., **39**, 203–207 (1934).

[1277] Price, A. T. Electromagnetic induction in a conducting sphere. Proc. Math. Soc., London, **31**, 217–224 (1929); **33**, 233–245 (1930).

[1278] Schlomka, T. Zur physikalischen Theorie des Erdmagnetismus. Zs. Geophysik, **9**, 99–109 (1933). [See also Beitr. Geophysik, **38**, 357–406 (1933).]

[1279] Schmidt, Ad. Zur Frage der elektrischen Vertikalströme. Zs. Geophysik, **1**, 281–284 (1924–25).

[1280] Schuster, A. British Association at Belfast, 1902, Section A, Subsection on Astronomy and Cosmical Physics. Opening address. Nature, **66**, 614–618 (1902). Abstract with detailed comment by J. Hann, Met. Zs., **20**, 19–30 (1903). [The address deals with the investigation of periodicities in geophysical phenomena.]

[1280-*A*] Venske, O. Ueber ein Vertikalvariometer mit Eisenstäben. Berlin, Veröff. Met. Inst., No. 290 (60)–(67) (1916). [In appendix of Bericht über die Tätigkeit des Preuss. Met. Inst., 1915.]

[1281] Walker, W. The magnetism of ships and the mariner's compass. London (1853).

(*B-a* to *B-g*) *Terrestrial electricity*

[1282] Adel, A., and C. O. Lampland. A new band in the absorption spectrum of the Earth's atmosphere. Astroph. J., **87**, 198–203 (1938).

[1283] Bauer, L. A. Correlations between solar activity and atmospheric electricity. Terr. Mag., **29**, 23–32, 161–186 (1924).

[1284] Bradbury, N. E. Photoelectric currents in gases between parallel plates as a function of the potential difference. Phys. Rev., **40,** 980–987 (1932).

[1285] Bradbury, N. E. Electron attachment and negative ion formation in oxygen and oxygen mixtures. Phys. Rev., **44,** 883–890 (1933).

[1286] Bureau, R. Électricité atmosphérique et parasites atmosphériques. Trans. Edinburgh Meeting, 1936; Internat. Union Geod. Geophys., Ass. Terr. Mag. Electr., Bull. No. 10, 429–436 (1937).

[1287] Collins, G. N., L. H. Flint, and J. W. McLane. Electric stimulation of plant growth. J. Agric. Res., **38,** 585–600 (1929).

[1288] Elster, J., and H. Geitel. Über eine fernere Analogie in dem elektrischen Verhalten der natürlichen und der durch Becquerelstrahlen abnorm leitend gemachten Luft. Physik. Zs., **2,** 590–593 (1901).

[1289] Erickson, H. A. Factors affecting the nature of ions in air. Phys. Rev., **34,** 635–643 (1929).

[1290] Gardner, M. E. The recombination of ions in pure oxygen as a function of pressure and temperature. Phys. Rev., **53,** 75–83 (1938).

[1291] Griffiths, E., and J. H. Aubery. The dependence of the mobility of ions in air on the relative humidity. Proc. Phys. Soc., **41,** 240–247 (1929).

[1292] Harper, W. R. On the theory of the combination coefficients for large ions and for uncharged particles at any pressure. Phil. Mag., **18,** 97–113 (1934). [For correction see Cambridge, Proc. Phil. Soc., **31,** 429–430 (1935).]

[1293] Hogg, A. R. Aitken condensation nuclei. Nature, **128,** 908 (1931).

[1294] Landsberg, H. The environmental variation of condensation-nuclei. Bull. Amer. Met. Soc., **18,** 172 (1937). [For thorough review of the literature on the nuclei of condensation in the atmosphere see Ergebnisse der kosmischen Physik, **3,** 155–252 (1938).]

[1295] Langevin, P., and M. Moulin. Sur un enregistreur des ions de l'atmosphère. C.-R. Acad. sci., **140,** 305–307 (1905).

[1296] Loeb, L. B. Kinetic theory of gases. New York, McGraw-Hill Book Company, Inc., xvi + 555 pp. (1927). 2d ed. (1934).

[1297] Loeb, L. B. Theory of recombination of ions over an extended pressure range. Phys. Rev., **51,** 1110–1111 (1937).

[1298] National Geographic Society. The National Geographic Society-U. S. Army Air Corps stratosphere flight of 1935 in the balloon *Explorer II*. Nation. Geog. Soc., Contrib. Tech. Papers, Stratosphere Ser., No. 2, 278 pp. (1936).

[1299] Przibram, K. Die Ionen in Gasen. Handbuch der Physik, herausgegeben von H. Geiger und K. Scheel, 2 Aufl., **22,** I, 343–423 (1933).

[1300] Schweidler, E. Die Ionenleitung in Gasen. Handbuch der Experimentalphysik, herausgegeben von H. Geiger und K. Scheel, **13,** I, 3–105 (1929).

[1301] Shaw, P. E., and R. F. Handstock. Triboelectricity and friction—V. On surface strain and relaxation of like solids. Proc. R. Soc., A, **128,** 474–487 (1930).

[1302] Thomson, J. J., and G. P. Thomson. Conduction of electricity through gases. Cambridge, University Press, 3d ed., 2 vols. (1928–1933).

[1303] Wait, G. R. Preliminary note on the effect of dust, smoke, and relative humidity upon the potential gradient and the positive and negative conductivities of the atmosphere. Terr. Mag., **32,** 31–35 (1927).

[1304] Wait, G. R. The intermediate ion of the atmosphere. Phys. Rev., **48,** 383 (1935).

[1305] Wait, G. R., and J. W. Mauchly. World-wide changes in potential gradient. Trans. Amer. Geophys. Union, 18th Annual Meeting, I, 169–170 (1937).

[1306] Zeleny, J. The velocity of ions produced in gases by Röntgen rays. Phil. Trans. R. Soc., A, **195**, 193–234 (1900).

(*B-h*) *Aurora*

[1307] Aars, J. Über die Aenderung des Kathodenstrahlenspektrums des Stickstoffs durch Kühlung mit flüssiger Luft. Ann. Physik, **1**, 216–228 (1929).

[1308] Angenheister, G. Das Polarlichtspektrum und die Konstitution der oberen Atmosphäre. Zs. Geophysik, **1**, 70–74 (1924).

[1309] Babcock, H. D. A study of the green auroral line by the interference method. Astroph. J., **57**, 209–221 (1923).

[1310] Baschin, O. Die ersten Nordlichtphotographien, aufgenommen in Bossekop (Lappland). Met. Zs., **17**, 278–280 (1900).

[1311] Bauer, W. Ultrarote Nordlichtphotographie. Naturw., **20**, 287–288 (1932).

[1311-*A*] Bernard, R. Étude interférentielle de la radiation jaune λ5893 Å du ciel crépusculaire et preuve de la présence du sodium dans la haute atmosphère. C.-R. Acad. sci., **206**, 928–930 (1938).

[1312] Birkeland, Kr. Sur les rayons cathodiques sous l'action de forces magnétiques intenses. Arch. Sci. Phys., **1**, 497–512 (1896).

[1313] Birkeland, Kr. Recherches sur les taches du Soleil et leur origine. Kristiania, Skr. Vid. selsk., I, No. 1, 173 pp., 13 pls. (1899).

[1314] Brüche, E., and W. Ende. Demonstrationsversuche zu Störmers Polarlichttheorie. Physik. Zs., **31**, 1015–1016 (1930); Zs. Physik, **64**, 186–190 (1930).

[1314-*A*] Cabannes, J., and J. Dufay. Analyse spectrale de la lumière du ciel nocturne au Pic du Midi. C.-R. Acad. sci., **198**, 306–309 (1934). [See also *ibid.*, **200**, 878–880, 1504–1506 (1935); **201**, 696–699 (1935).]

[1314-*B*] Cabannes, J., and J. Dufay. Sur la radiation jaune du ciel nocturne. C.-R. Acad. sci., **206**, 221–224 (1938).

[1314-*C*] Cabannes, J., J. Dufay, and J. Gauzit. Sur la présence du sodium dans la haute atmosphère. C.-R. Acad. sci., **206**, 870–872 (1938).

[1315] Chapman, S. The correlation of solar and terrestrial phenomena. Nature, **121**, 989–991 (1928).

[1316] Frerichs, R. The singlet system of the oxygen arc spectrum and the origin of the green auroral line. Phys. Rev., **36**, 398–409 (1930).

[1317] Goldstein, E. Über die Entladung der Elektrizität in verdünnten Gasen. Wied. Ann., **12**, 266 (1881).

[1318] Harang, L. Über das Auftreten eines besonderen Nordlichtbogens am 26. Januar 1931. Zs. Geophysik, **7**, 271–274 (1931).

[1319] Harang, L. An apparatus for registration of the Aurora Borealis. Terr. Mag., **37**, 167–168 (1932).

[1320] Harang, L. Eine Untersuchung der Polarisation des Nordlichtes. Zs. Geophysik, **9**, 162–164 (1933).

[1321] Hopfield, J. J. Revised values of OI terms, nebular and coronal lines of oxygen. Phys. Rev., **37**, 160–166 (1931).

[1321-*A*] Kosirev, N. A., and D. J. Eropkin. Spectrophotometry of Aurora Borealis with special reference to the sunlit aurorae. Poulkovo Obs. Cir., No. 18, 25–29 (1936).

[1322] Krogness, O., and L. Vegard. Höhenbestimmungen des Nordlichts an dem Haldde observatorium von Oktober 1912 bis Anfang Januar 1913. Kristiania, Skr. Vid. selsk., I, No. 11, 30 pp. (1914).

[1323] Lenard, L. Über die Absorption der Nordlichtstrahlen in der Erdatmosphäre. Heidelberg, SitzBer. Ak. Wiss., Abh. 12, 9 pp. (1911).

[1324] Loomis, E. The Aurora Borealis. (1869).

[1325] McLennan, J. C., H. J. C. Ireton, and K. Thomson. The luminescence of solid nitrogen under cathode-ray bombardment. Proc. R. Soc., A, **116,** 1–15 (1927).

[1326] McLennan, J. C., J. H. McLeod, and W. C. McQuarrie. An investigation into the nature and occurrence of the auroral green line λ 5577 Å. Proc. R. Soc., A, **114,** 1–22 (1927).

[1327] McLennan, J. C., and G. M. Shrum. On the luminescence of nitrogen, argon, and other condensed gases at very low temperatures. Proc. R. Soc., A, **106,** 138–149 (1924).

[1328] McLennan, J. C., and G. M. Shrum. On the origin of the auroral green line 5577 Å, and other spectra associated with the Aurora Borealis. Proc. R. Soc., A, **108,** 501–512 (1925).

[1329] Mairan, J. J. Traité physique et historique de l'aurore boréale. Paris, Mém. Acad. R. Sci., (1733); 2d ed. (1754).

[1330] Milne, E. A. On the possibility of the emission of high-speed atoms from the Sun and stars. Mon. Not. R. Astr. Soc., **86,** 459–473 (1926).

[1331] Paschen, F. Das Sauerstoffspektrum OI. Zs. Physik, **65,** 1–3 (1930).

[1332] Ramanathan, K. R., and J. V. Karandikar. Spectrum of the night sky and of the zodiacal light. Nature, **132,** 749 (1933).

[1333] Rayleigh, Lord. A photographic spectrum of the aurora of May 13–15, 1921, and laboratory studies in connection with it. Proc. R. Soc., A, **101,** 114–124, 312–315 (1922).

[1334] Rosseland, S. On the theory of the chromosphere and the corona. Avh. Norske Vid. Akad., I, No. 1, 37 pp. (1933).

[1335] Rosseland, S., and G. Steensholt. On the relative intensity of bands in a sequence and the temperature of the upper atmosphere. Avh. Norske Vid. Akad., I, No. 5, 17 pp. (1933).

[1336] Slipher, V. M. On the general auroral illumination of the sky and the wavelength of the chief auroral line. Astroph. J., **49,** 266–275 (1919).

[1337] Slipher, V. M., and L. A. Sommer. Zur Deutung des Nordlichtspectrums. Naturw., **17,** 802–803 (1929). [See also L. Vegard, *ibid.*, 980–981 (1929).]

[1338] Störmer, C. Sur les trajectoires des corpuscules électrisés dans l'espace sous l'action du magnétisme terrestre avec application aux aurores boréales. Arch. Sci. Phys., **24** (1907); **32** (1911); **33** (1912).

[1339] Störmer, C. Sur la situation de la zone de fréquence maximum des aurores boréales d'après la théorie corpusculaire. C.-R. Acad. sci., **151,** 736–739 (1910).

[1340] Störmer, C. Remarques sur la note de M. Kr. Birkeland, relative à l'origine des planètes et de leurs satellites. C.-R. Acad. sci., **155,** 1073–1075 (1912). [See also *ibid.*, **156,** 450–453, 536–539 (1913); **162,** 829–832 (1916).]

[1341] Störmer, C. Résultats des calculs numériques des trajectoires des corpuscules électriques dans le champ d'un aimant élémentaire. Kristiania, Skr. Vid. selsk., I, No. 4, 73 pp., 2 pls. (1913); No. 10, 58 pp., 8 pls. (1913); No. 14, 64 pp., 15 pls. (1913).

[1342] Störmer, C. On an auroral expedition to Bossekop in the spring of 1913. Terr. Mag. **18,** 133–135 (1913); **20,** 1–12, 159–174 (1915); **21,** 45–68, 153–156 (1916).

[1343] Störmer, C. Sur un problème relatif au mouvement des corpuscules électriques dans l'espace cosmique. Kristiania, Skr. Vid. selsk., I, No. 6, 60 pp. (1916); No. 12, 91 pp., 45 pls. (1916).

[1344] Störmer, C. The altitude of Aurora Borealis seen from Bossekop during the spring of 1913. Astroph. J., **43,** 243–245 (1916).

[1345] Störmer, C. Sur les draperies d'aurores boréales. Arch. Sci. Phys., **43,** 285–294 (1917).

[1346] Störmer, C. The importance of taking aurora photographs from a network of stations around the Polar Basin in collaboration with Roald Amundsen's Expedition. Geofys. Pub., **1,** No. 4, 25–27 (1920).

[1347] Störmer, C. Extract from a report on the Northern Lights Expedition to Bossekop—Store Korsnes in the spring of 1913. Geofys. Pub., **1,** No. 4, 19–24 (1920).

[1348] Störmer, C. An effect of sunlight on the altitude of aurora rays. Nature, **120,** 329–330 (1927). [See also *ibid.,* **123,** 82–83, 868–869 (1929); **124,** 263–264 (1929); **125,** 305 (1930).]

[1349] Störmer, C. Action remarquable de la lumière du Soleil sur la hauteur des aurores boréales. C.-R. Acad. sci., **185,** 261–263 (1927).

[1350] Störmer, C. Vom Jahre 1922 an im südlichen Norwegen aufgenommene Nordlichtphotogramme. Zs. Geophys., **4,** 261–263 (1928).

[1351] Störmer, C. Angenäherte Integration der Bewegungsgleichungen von Elektronen im Felde eines magnetischen Dipols. Zs. Astroph., **6,** 333–344 (1933).

[1352] Störmer, C. Height and velocity of luminous night-clouds observed in Norway 1932. Avh. Norske Vid. Akad., I, No. 2, 45 pp., 10 pls. (1933).

[1352-*A*] Störmer, C. Altitudes and spectra of red and sunlit auroras. Nature, **139,** 584 (1937). [See also *ibid.,* **140,** 1095–1096 (1937).]

[1353] Swinne, R. Zur Absorption solarer positiver (Nordlicht-) Strahlen in der Erdatmosphäre. Physik. Zs., **17,** 529–532 (1916).

[1354] Sykora, J. Observations directes et photographiques des aurores boréales. St. Pétersbourg, Mém. Acad. sci., Sér. 8, **14,** No. 5.

[1355] Tromholt, S. Sur les périodes de l'aurore boréale. Copenhagen (1882).

[1356] Vegard, L. Über die Lichterzeugung in Glimmlicht und Kanalstrahlen. Ann. Physik, **39,** 111–169 (1912).

[1357] Vegard, L. On the properties of the rays producing Aurora Borealis. Phil. Mag., **23,** 211–237 (1912). [See also Arch. Math. Naturv., Nos. 6 and 9 (1911), and Nature, **86,** 212–213 (1911).]

[1358] Vegard, L. Photographische Aufnahmen des Nordlichtspektrums mit einem Spectrographen von grosser Dispersion. Physik. Zs., **14,** 677–681 (1913).

[1359] Vegard, L. The auroral expedition 1912–13. Vid. Akad. Skr., I, No. 13 (1916).

[1360] Vegard, L. Nordlichtuntersuchungen. Über die physikalische Natur der kosmischen Strahlen, die das Nordlicht hervorrufen. Ann. Physik, **50,** 853–900 (1916).

[1361] Vegard, L. The determination of the wave length of the green line of the auroral spectrum. Geofys. Pub., **2,** No. 5, 11 pp. (1922).

[1362] Vegard, L. Sur le spectre de l'aurore boréale et les couches supérieures de l'atmosphère. C.-R. Acad. sci., **176,** 947–950, 1488–1491 (1923).

[1363] Vegard, L. Light emitted from solid nitrogen when bombarded with cathode rays, and its bearing on the auroral spectrum. Amsterdam, Proc. Sci., K. Akad. Wet., **27,** 113–126 (1924).

[1364] Vegard, L. Das Nordlicht. Handb. der Radiologie, **4,** 505 (1925).

[1365] Vegard, L. The auroral spectrum and the upper atmosphere. Nature, **113,** 716–717 (1924); **118,** 801 (1926).

[1366] Vegard, L. The origin of the red colour of the aurora of January 26, 1926. Oslo, Skr. Vid. selsk., I, No. 2, 5 pp. (1926). [See also Nature, **117,** 356 (1926).]

[1367] Vegard, L. Das Leuchten verfestigter Gase und seine Beziehungen zu kosmischen Vorgängen. Ann. Physik, **79,** 377–441 (1926); **6,** 487–544 (1930).

[1368] Vegard, L. Spectrographic observations of the second green line of the auroral spectrum. Nature, **119**, 349–350 (1927). [See also Avh. Norske Vid. Akad., I, No. 2 (1927).]

[1369] Vegard, L. Results of observations from the solar eclipse in Norway, June 29, 1927, and the constitution of the solar corona and sunspots. Oslo, Skr. Vid. Akad., I, No. 2, 36 pp. (1928).

[1370] Vegard, L. Variations of intensity distribution of the auroral spectrum and the possible influence of sunlight. Nature, **124**, 947–948 (1929).

[1371] Vegard, L. Zur Deutung des Nordlichtspektrums. Naturw., **17**, 980–981 (1929).

[1372] Vegard, L. Die Korona der Erde und Sonne und ihre Beziehung zu kosmischen Erscheinungen. Beitr. Geophysik, **32**, 288–300 (1931).

[1373] Vegard, L. The temperature of the auroral region determined by the rotational series of the negative nitrogen-bands. Terr. Mag., **37**, 389–398 (1932).

[1374] Vegard, L. Results of investigations of the auroral spectrum during the years 1921–1926. Geofys. Pub., Oslo, **9**, No. 11, 71 pp., 4 pls. (1932).

[1375] Vegard, L. Spektralaufnahmen von ultraroten Linien im Nordlichtspektrum. Naturw., **20**, 268–269 (1932).

[1376] Vegard, L. Wave-length of the green auroral line determined by the interferometer. Nature, **129**, 23 (1932).

[1377] Vegard, L. Ergebnisse fortgesetzter Untersuchungen über das Leuchten verfestigter Gase. Beziehungen zu den Elektronenzuständen und dem Nachleuchten des gasförmigen Stickstoffs. Zs. Physik, **75**, 30–62 (1932).

[1378] Vegard, L. Der sichtbare Teil des Nordlichtspektrums. Zs. Physik, **78**, 567–575 (1932); **81**, 556–559 (1933).

[1379] Vegard, L. Investigations of the auroral spectrum based on observations from the Auroral Observatory, Tromsö. Geofys. Pub., **10**, No. 4, 61 pp., 3 pls. (1933).

[1380] Vegard, L. The auroral spectrum and the upper atmosphere. Nature, **132**, 682 (1933).

[1380-*A*] Vegard, L. Red and sunlit auroras and the state of the upper atmosphere. Nature, **138**, 930–931 (1936).

[1380-*B*] Vegard, L. Vorgänge und Zustände in der Nordlichtregion. Geofys. Pub., **12**, No. 5, 23 pp., 2 pls. (1938).

[1380-*C*] Vegard, L. Altitude effects in the red part of the auroral spectrum and the two types of red auroras. Nature, **141**, 200 (1938).

[1381] Vegard, L., and L. Harang. The auroral spectrum in the region of long waves. Geofys. Pub., **10**, No. 5, 13 pp. (1933).

[1381-*A*] Vegard, L., and L. Harang. The wave-length of the green auroral line determined by an interferometer method. Geofys. Pub., **11**, No. 1, 17 pp., 3 pls. (1934).

[1381-*B*] Vegard, L., and L. Harang. Recent results regarding the spectral analysis of the auroral luminescence. Geofys. Pub., **11**, No. 15, 23 pp., 4 pls. (1937).

[1382] Vegard, L., and O. Krogness. The height of the Aurora Borealis according to observations at the Haldde Observatory, Norway. Terr. Mag., **21**, 169–174 (1916). [See also C.-R. Acad. sci., **163**, 442–446 (1916); Ann. Physik, **51**, 495–502 (1916).]

[1383] Vegard, L., and E. Tönsberg. The temperature of the auroral region determined from band spectra. Geofys. Pub., Oslo, **12**, No. 3, 9 pp., 2 pls. (1938).

[1383-*A*] Vegard, L., and E. Tönsberg. Die spektrale Intensitätsverteilung im Nachthimmellicht und Nordlicht. Zs. Physik, **88**, 709–726 (1934); **94**, 413–433 (1935).

[1383-*B*] Vegard, L., and E. Tönsberg. Continued investigations on the temperature of the upper atmosphere determined by means of bands appearing in the auroral spectrum. Geofys. Pub., **11**, No. 2, 14 pp. (1935).

[1383-*C*] Vegard, L., and E. Tönsberg. Enhancement of red lines and bands in the auroral spectrum from a sunlit atmosphere. Nature, **137,** 778–779 (1936).

[1383-*D*] Vegard, L., and E. Tönsberg. Variations of intensity distribution within the auroral spectrum. Geofys. Pub., **11,** No. 16, 36 pp. (1937).

[1384] Villard, P. Sur l'aurore boréale. C.-R. Acad. sci., **142,** 1330–1333 (1906); **143,** 143–145, 587–589 (1906). [See also volumes of Le Radium for 1906 and 1907.]

[1385] Wegener, K. Das Polarlicht in Spitzbergen nach photogrammetrischen Messungen 1912/13. Strassburg, Schr. Wiss. Ges., Heft 21, 30–65 (1914).

(*B-i*) *Earth-currents*

[1386] Airy, G. B. Comparison of magnetic disturbances on Greenwich self-recording magnetographs with disturbances of the terrestrial galvanic currents. Phil. Trans. R. Soc., **158,** II, 465–473 (1868).

[1387] Barlow, W. H. On the spontaneous electric currents observed in the wires of the electric telegraph. Phil. Trans. R. Soc., 61 (1849).

[1388] Bartels, J., and W. J. Rooney. A typical case of variability of the quiet-day diurnal variation in terrestrial magnetism and earth-currents at Watheroo. Terr. Mag., **37,** 53–55 (1932).

[1389] Bauer, L. A. Relations between the diurnal and annual variations of earth-currents, terrestrial magnetism, and atmospheric electricity. Terr. Mag., **28,** 129–140 (1923).

[1390] Chapman, S., and T. T. Whitehead. On the observations of earth potential-gradients at Ebro. Terr. Mag., **28,** 125–128 (1923).

[1391] Gish, O. H. On anomalous earth-currents in mountain-regions. Washington, D. C., Carnegie Inst., Year Book No. 30, 344–345 (1931).

[1392] Gish, O. H. The anomalous mountain-effect in earth-current measurements. Terr. Mag., **37,** 407–408 (1932).

[1393] Gish, O. H. The problem of vertical earth-currents. Trans. Amer. Geophys. Union, 14th Annual Meeting, 144–146 (1933).

[1394] Gish, O. H., W. J. Rooney, and A. K. Ludy. Earth-current observations on long lines in southern Arizona. Washington, D. C., Carnegie Inst., Year Book No. 30, 347–348 (1931).

[1395] King, L. V. On the flow of electric current in semi-infinite media in which the specific resistance is a function of the depth. Phil. Trans. R. Soc., A, **233,** 327–359 (1934); Proc. R. Soc., A, **139,** 237–277 (1933).

[1396] Koenigsberger, J. G. On the vertical component of the earth-current in mountainous regions. Terr. Mag., **37,** 406 (1932).

[1397] Mollá, J. G. Courants telluriques. La Section Électrique, Mém. Obs. de l'Èbre, No. 4, 95–119 (1910).

[1398] Schuster, A. On the interpretation of earth-current observations. Terr. Mag., **3,** 130–131 (1898).

[1399] Stenquist, D. Étude des courants telluriques. Mémoires publiés par la Direction Générale des Télégraphes de Suède, 79 pp. (1925). Fasc. 2, 17 pp. (1930).

[1400] Ubach, J. Corrientes telúricas. Bol. Mens. Obs. del Ebro, **1,** 51–55 (1910). [Text in Spanish and French.]

(*C*) *Geophysical prospecting*

[1401] Aldrich, H. R. A demonstration of the reflection of geologic conditions in observed magnetic intensity. Geophysical Prospecting 1929; Trans. Amer. Inst. Min. Metall. Eng., **81,** 385–400 (1929).

[1402] Barret, W. M. A method for determining magnetic susceptibility of core samples. Geophysical Prospecting 1932; Trans. Amer. Inst. Min. Metall. Eng., **97,** 216–233 (1932). [On pp. 234–236, C. A. Heiland discusses "Applicability of method" and "Important methods for determining magnetic susceptibility."]

[1403] Barret, W. M. Magnetometer practice in the field. Oil Gas J., **28** (October 10, 1929).

[1404] Ebert, A. Aufsuchen von vergrabener Munition durch magnetische und elektrische Messungen. Beitr. Geophysik, Ergänzungshefte angew. Geophysik, **1,** 9–14 (1930).

[1405] Ehrenburg, D. O., and R. J. Watson. Mathematical theory of electrical flow in stratified media with horizontal, homogeneous and isotropic layers. Geophysical Prospecting 1932; Trans. Amer. Inst. Min. Metall. Eng., **97,** 423–438, discussion, 438–442 (1932).

[1406] Grohskopf, J. G., and C. O. Reinoel. Missouri Bureau of Geology and Mines, Appendix IV, 57 Biennial Report, 20 pp. (1933). [Contains results of surveys to determine the magnetic anomalies near some of the principal structural features.]

[1407] Heiland, C. A., and W. H. Courtier. Magnetometric investigation of gold placer deposits near Golden, Colo. Geophysical Prospecting 1929; Trans. Amer. Inst. Min. Metall. Eng., **81,** 364–384 (1929).

[1408] Heiland, C. A., and W. E. Pugh. Theory and experiments concerning a new compensated magnetometer system. Geophysical Prospecting 1934; Trans. Amer. Inst. Min. Metall. Eng., **110,** 334–372 (1934).

[1409] Hummel, J. N. A theoretical study of apparent resistivity in surface potential methods. Geophysical Prospecting 1932; Trans. Amer. Inst. Min. Metall. Eng., **97,** 392–422 (1932).

[1409-*A*] Kohl, E. Ueber die magnetische Störwirkung von Eisenkörpern und Eisenmassen (Schachtanlagen, Bohreinrichtungen, usw.). Kali, **24,** No. 12, 13, and 14, 93–120, 177–181, 212–216 (1930).

[1410] Lee, F. W. Some comments upon applied geophysics in the past year, 1933. Terr. Mag., **39,** 127–131 (1934).

[1410–*A*] Lundberg, H. Recent advances in geophysical prospecting. Canadian Min. Met. Bull., No. 308, 758–788 (1937).

[1411] Malamphy, M. C. Magnetic measurements on auriferous veins in Brazil. Geophysical Prospecting 1934; Trans. Amer. Inst. Min. Metall. Eng., **110,** 313–325 (1934).

[1412] Muskat, M. Potential distribution about an electrode on the surface of the Earth. Physics, **4,** 129–147 (1933).

[1413] Roman, I. How to compute tables for determining electrical resistivity of underlying beds and their application to geophysical problems. Washington, D. C., U. S. Bur. Mines, Tech. Paper 502, 44 pp. (1931).

[1414] Roman, I. The calculation of electrical resistivity for a region underlying two uniform layers. Terr. Mag., **38,** 117–140, 185–202 (1933).

[1415] Roman, I., and T. C. Sermon. A magnetic gradiometer. Geophysical Prospecting 1934; Trans. Amer. Inst. Min. Metall. Eng., **110,** 373–387 (1934).

[1416] Schroeder, R., and H. Reich. Magnetische Untersuchung eines Basaltsteinbruchgeländes. Beitr. Geophysik, Ergänzungshefte angew. Geophysik, **1,** 432–436 (1931).

[1417] Slichter, L. B. Certain aspects of magnetic surveying. Geophysical Prospecting 1929; Trans. Amer. Inst. Min. Metall. Eng., **81,** 238–258 (1929).

[1418] Slichter, L. B. The interpretation of the resistivity prospecting method for horizontal structures. Physics, **4,** 307–322 (1933). [See also *ibid.,* 411–418.]

[1419] Stearn, N. H. A background for the application of geomagnetics to exploration. Geophysical Prospecting 1929; Trans. Amer. Inst. Min. Metall. Eng., **81,** 315–344 (1929).

[1420] Stearn, N. H. Practical geomagnetic exploration with the Hotchkiss superdip. Geophysical Prospecting 1932; Trans. Amer. Inst. Min. Metall. Eng., **97,** 169–197 (1932).

[1421] Stevenson, A. F. On the theoretical determination of earth-resistance from surface potential measurements. Phil. Mag., **19,** 297–306 (1935).

[1422] Tagg, G. F. Interpretation of resistivity measurements. Geophysical Prospecting 1934; Trans. Amer. Inst. Min. Metall. Eng., **110,** 135–144 (1934).

[1423] Van Weelden, A. Regional tectonical feature of the Wichita-Arbuckle mountain region in the light of geophysical observation. Proc. World Petrol. Cong., **1,** 174–176 (1934).

[1424] Weaver, W. Certain applications of the surface potential method. Geophysical Prospecting 1929; Trans. Amer. Inst. Min. Metall. Eng., **81,** 68–83, discussion 83–86 (1929).

(*D*) *Ionosphere and upper atmosphere*

[1425] Abbot, C. G. A group of solar changes. Smithsonian Inst., Misc. Collect., **80,** No. 2, 16 pp. (1927).

[1426] American URSI broadcasts of cosmic data. Terr. Mag., **35,** 184–185 (1930) and subsequently in each quarterly issue of that journal. [These announcements contain data for terrestrial magnetism, sunspots, solar constant, Kennelly-Heaviside layer heights, and beginning with **42,** 316–319 (1937) American magnetic character-numbers are regularly included.]

[1427] Appleton, E. V. Wireless studies of the ionosphere. J. Inst. Elec. Eng., **71,** 642–650 (1932).

[1428] Bacher, R. F., and S. Goudsmit. Atomic energy states—as derived from analyses of optical spectra. New York, McGraw-Hill Book Company, Inc., xiii + 562 pp. (1932).

[1429] Barnard, E. E. Drifting meteor trains. Sidereal Messenger, **1,** 174–180 (1882).

[1430] Barnard, E. E. The gegenschein and its possible origin. Pop. Astr., **27,** 109–112 (1919). [See also *ibid.,* **7,** 169 (1899).]

[1431] Bartels, J. Die höchsten Atmosphärenschichten. Ergeb. Exakt. Naturw., **7,** 114–157 (1928).

[1432] Benndorf, H. Über die experimentelle Erforschbarkeit der höheren Schichten der Atmosphäre. Physik. Zs., **30,** 97–115 (1929).

[1433] Bontch-Bruewitch, M. A. Ionospheric measurements in the polar regions. Nature, **133,** 175–176 (1934).

[1434] Bradbury, N. E. Electron attachment and negative ion formation in oxygen and oxygen mixtures. Phys. Rev., **44,** 883–890 (1933).

[1435] Breit, G. Group velocity and long retardations of radio echoes. Proc. Inst. Radio Eng., **17,** 1508–1512 (1929).

[1436] Breit, G., M. A. Tuve, and O. Dahl. Effective heights of the Kennelly-Heaviside layer in December, 1927, and January, 1928. Proc. Inst. Radio Eng., **16,** 1236–1239 (1928).

[1437] Chapman, S. The lunar tide in the Earth's atmosphere. Q. J. R. Met. Soc., **45,** 113–139 (1919); Nature, **103,** 185–187 (1919).

[1438] Chapman, S. The influence of a solar eclipse upon upper atmospheric ionization. Mon. Not. R. Astr. Soc., **92,** 413–420 (1932). [See also *ibid.,* 421–422 (1932).]

[1439] Chapman, S. Solar influences on the Earth's magnetism and on the upper atmosphere. Conseil Internat. Unions Scientifiques, Quatrième Rapport, Comm. Relations Solaires et Terrestres, 54–59 (1936).

[1440] Darrow, K. K. Electrical phenomena in gases. Baltimore, Williams & Wilkins Company, xvii + 492 pp. (1932).

[1441] Eckersley, T. L. Irregular ionic clouds in the *E*-layer of the ionosphere. Nature, **140,** 846–847 (1937).

[1442] Elvey, C. T. Photometry of the gegenschein. Astroph. J., **77,** 56–62 (1933). [See also *ibid.,* **75,** 424–426 (1932).]

[1443] Eropkin, D., and N. Kozirew. Spectrophotometry of the night sky and zodiacal light. Poulkovo Obs. Cir., No. 13, 21–26 (1935).

[1444] Fabry, C. The absorption of radiation in the upper atmosphere. Proc. Phys. Soc., **39,** 1–14 (1926).

[1445] Fath, E. A. The spectrum of the zodiacal light. Lick Obs. Bull., **5,** 141–143 (1909).

[1446] Fowler, R. H. Dissociation-equilibria by the method of partitions. Phil. Mag., **45,** 1–33 (1923).

[1447] Frankenberger, E. Hochfahrten von Registrierballonen. Ann. Hydrogr., **59,** 20–22 (1931).

[1448] Gardner, M. E. The coefficient of recombination of pure oxygen as a function of pressure and temperature. Abstract, Phys. Rev., **51,** 144 (1937).

[1449] Gaunt, J. A. Continuous absorption. Phil. Trans. R. Soc., A, **229,** 163–204 (1930). [Contains a critical discussion of the opacity-formulas of Milne, Eddington, Oppenheimer, and Rosseland.]

[1450] Gilliland, T. R. Continuous measurements of the virtual heights of the ionosphere. Bur. Stan. J. Res., **11,** 141–146 (1933); Proc. Inst. Radio Eng., **21,** 1463–1475 (1933).

[1451] Gilliland, T. R. Note on a multifrequency automatic recorder of ionospheric heights. Bur. Stan. Res. J., **11,** 561–566 (1933); Proc. Inst. Radio Eng., **22,** 236–246 (1934).

[1452] Goubau, G., and J. Zenneck. Messung von Echos bei der Ausbreitung elektromagnetischer Wellen in der Atmosphäre. Zs. Hochfrequenztech., **37** , 207–218 (1931).

[1453] Gowan, E. H. The effect of ozone on the temperature of the upper atmosphere. Proc. R. Soc., A, **120,** 655–669 (1928); **128,** 531–550 (1930).

[1454] Green, A. L. The polarization of sky waves in the Southern Hemisphere. Proc. Inst. Radio Eng., **22,** 324–343 (1934).

[1455] Gussev, P. J. On the new index of solar activity. Poulkovo Obs. Cir., No. 10, 3–6 (1934).

[1456] Gutenberg, B. Schallgeschwindigkeit und Temperatur in der Stratosphäre. Beitr. Geophysik, **27,** 217–225 (1930).

[1457] Hall, M. The zodiacal light. Mon. Weath. Rev., **34,** 126–131 (1906).

[1458] Halm, J. On the rotation of the Sun's reversing layer. Mon. Not. R. Astr. Soc., **82,** 479–483 (1922).

[1459] Henderson, J. T. Measurements of ionization in the Kennelly-Heaviside layer during the solar eclipse of 1932. Canadian J. Res., **8,** 1–14 (1933).

[1460] Hergesell, H., and P. Duckert. Die Ergebnisse der Sprengungen zu Forschungszwecken in Deutschland, 1923–1929. Arbeiten Aeronaut. Obs. Lindenberg, **16,** *B,* 55 pp. (1927); **16,** *D,* 32 pp. (1930).

[1461] Hulburt, E. O. The zodiacal light and the gegenschein as phenomena of the Earth's atmosphere. Phys. Rev., **35,** 1098–1118 (1930).

[1462] Hulburt, E. O. Atmospheric ionization by cosmic radiation. Phys. Rev., **37,** 1–8 (1931).

[1463] Hulburt, E. O. Ionization in the upper atmosphere at about 200 km above sea level. Physics, **4,** 196–201 (1933).

[1464] Hulburt, E. O. Analysis of recent measurements of the ionosphere. Phys. Rev., **46,** 822–823 (1934).

[1465] Hulburt, E. O. Photoelectric ionization in the ionosphere. Phys. Rev., **53,** 344–351 (1938).

[1466] Hulburt, E. O. The brightness of the twilight sky and the density and temperature of the atmosphere. J. Optical Soc. Amer., **28,** 227–236 (1938).

[1467] Jeans, J. H. Astronomy and cosmogony. Cambridge, University Press, x + 420 pp. (1928).

[1468] Johnson, T. H. Contribution of the cosmic radiation to the ionization of the upper atmosphere. Trans. Amer. Geophys. Union, 16th Annual Meeting, I, 35–37 (1935).

[1469] Jones, G. Observations on the zodiacal light from April 2, 1853, to April 22, 1855. Washington, D. C., U. S. Japan Expedition, **3,** 1–705 (1856).

[1470] Judson, E. B. Comparison of data on the ionosphere, sunspots, and terrestrial magnetism. J. Res. Bur. Stan., **17,** 323–330 (1936).

[1471] Kahlke, S. Meteorschweife und hochatmosphärische Windströmungen. Ann. Hydrogr., **49,** 294–299 (1921). [See also E. O. Hulburt, Pub. Astr. Soc. Pacific, **44,** 178–182 (1932).]

[1472] Kaplan, J. The production of the auroral spectrum in the laboratory. Trans. Amer. Geophys. Union, 15th Annual Meeting, I, 162–166 (1934).

[1473] Kirby, S. S., N. Smith, T. R. Gilliland, and S. E. Reymer. The ionosphere and magnetic storms. Phys. Rev., **51,** 992–993 (1937).

[1474] Kramers, H. A. On the theory of X-ray absorption and of continuous X-ray spectrum. Phil. Mag., **46,** 836–871 (1923).

[1475] Leeuwen, Mlle. H. J. van. Problèmes de la théorie électronique du magnétisme. J. Phys. et Le Radium, **2,** 361–377 (1921).

[1476] Lepape, A., and G. Colange. Helium content of the stratosphere and of the air at the Earth's surface. Nature, **137,** 459 (1936).

[1477] Loeb, L. B. Ionic recombination in the ionosphere. Phys. Rev., **52,** 40–41 (1937).

[1478] Lorentz, H. A. Propagation of light in a body composed of molecules. The theory of electrons, 2d ed., Chapter 4, 132–167 (1916).

[1479] Lyman, T. The absorption of some gases for light of very short wave-length. Astroph. J., **27,** 87–105 (1908).

[1480] Maris, H. B. A theory of meteors. Terr. Mag., **34,** 309–316 (1929).

[1481] Milne, E. A. Statistical equilibrium in relation to the photoelectric effect, and its application to the determination of absorption coefficients. Phil. Mag., **47,** 209–241 (1924).

[1482] Milne, E. A. On the possibility of the emission of high-speed atoms from the Sun and stars. Mon. Not. R. Astr. Soc., **86,** 459–473, 578–599 (1926). [Also Handb. Astrophysik, **3,** I, 173–183, 316 (1930).]

[1483] Minohara, T., Y. Ito, S. Fujiwhara, and S. Imamichi. Ionospheric and magnetic records in Japan—VI (from October 1935 to April 1936). Rep. Radio Res. Japan, **6,** L1-L21 (1936).

[1484] Mitra, S. K., and P. Syam. Absorbing layer of the ionosphere at low height. Nature, **135,** 953–954 (1935).

[1485] Mohler, F. L. Recombination in the afterglow of a discharge. Phys. Rev., **51,** 1008–1009 (1937). [Abstract of paper before American Physical Society, April 29–May 1, 1937.]

[1486] Moulton, F. R. An introduction to celestial mechanics. 2d ed. New York, The Macmillan Company, xvi + 437 pp. (1914).

[1487] Murray, F. H., and J. B. Hoag. Heights of reflection of radio waves in the ionosphere. Phys. Rev., **51,** 333–341 (1937).

[1488] National Bureau of Standards. Characteristics of the ionosphere at Washington, D. C. A series of monthly reports beginning in Proc. Inst. Radio Eng., **25,** 1174–1191 (1937). [See also *ibid.,* **25,** 823–840 (1937).]

[1489] Newall, H. F. On the law of rotation of the Sun. Mon. Not. R. Astr. Soc., **82,** 101–114 (1921).

[1490] Newcomb, S. An observation of the zodiacal light to the north of the Sun. Astroph. J., **22,** 209–212 (1905). [Note by E. E. Barnard, *ibid.,* **23,** 168–169 (1906).]

[1491] O'Brien, B., F. L. Mohler, and H. S. Stewart. Vertical distribution of ozone in the upper atmosphere. Phys. Rev., **50,** 1099 (1936).

[1492] Pachine, C. Observations de la lumière zodiacale. Bul. Soc. Astr. France, **27,** 69–71 (1913).

[1493] Page, L. The motion of ions in constant fields. Phys. Rev., **33,** 553–558 (1929).

[1494] Page, L. Conductivity of ions in crossed electric and magnetic fields. Phys. Rev., **34,** 763–771 (1929).

[1495] Paneth, F. A., and E. Glückauf. Helium content of the stratosphere. Nature, **136,** 717–718 (1935).

[1496] Pannekoek, A. Ionization equilibrium in stellar atmospheres. Amsterdam, Proc. Sci., K. Akad. Wet., **29,** 1165–1171 (1926).

[1497] Perepelkin, E. J. On the relative intensity of the H_ϵ and H lines in the prominences and on its variations. Poulkovo Obs. Cir., No. 9, 2–11 (1933).

[1498] Prokofiev, G. A., and others. The Central Geophysical Observatory and the ascent into the stratosphere on September 30, 1933. Leningrad, 26 pp. (1934). Abstracted in Nature, **133,** 918–919 (1934).

[1499] Pulley, O. O. A self-synchronized system for ionospheric investigation by the pulse method. Proc. Phys. Soc., **46,** 853–871 (1934).

[1500] Ramanathan, K. R. A note on the general spectrum of the night sky as observed in India. Indian J. Phys., **7,** 405–410 (1932).

[1501] Ramanathan, K. R., and J. V. Karandikar. Spectrum of the night sky and of the zodiacal light. Nature, **132,** 749 (1933). [See also *ibid.,* **129,** 280, 545 (1932).]

[1502] Regener, E. Oxygen content of the stratosphere. Nature, **138,** 544 (1936).

[1503] Rose, D. C. Radio observations on the upper ionized layer at the time of the total solar eclipse of August 31, 1932. Canadian J. Res., **8,** 15–28 (1933).

[1504] Rosseland, S. On the theory of the chromosphere and the corona. Oslo, Avh. Norsk. Vid. Akad., No. 1, 37 pp. (1933).

[1505] Rosseland, S. Theoretical astrophysics. Oxford, Clarendon Press, xix + 355 pp. (1936).

[1506] Rukop, H., and P. Wolf. Eine leistungsfähige Einrichtung für Messungen an den Heavisideschichten. Zs. Tech. Physik, **13,** 132–134 (1932).

[1507] Russell, H. N., R. S. Dugan, and J. Q. Stewart. Astronomy. Volume I, The solar system. Boston, Ginn and Company, xi + 470 + xxi pp. (1926).

[1508] Saha, M. N. Ionization in the solar chromosphere. Phil. Mag., **40,** 472–488 (1920).

[1509] Schafer, J. P., and W. M. Goodall. Radio studies of the ionosphere. Nature, **132,** 521–522 (1933).

[1510] Shepherd, M. The composition of the atmosphere at approximately 21.5 kilometers. Nation. Geog. Soc., Contrib. Tech. Papers, Stratosphere Ser., No. 2, 117–133 (1936).

[1511] Skellett, A. M The ionizing effects of meteors. Proc. Inst. Radio Eng., **23,** 132–149 (1935).

[1512] Slipher, V. M. A preliminary note on the spectrum of the zodiacal light. Lowell Obs. Cir. (February 20, 1931).

[1513] Smith, N., and S. S. Kirby. Critical frequencies of low ionosphere layers. Phys. Rev., **51,** 890–891 (1937).

[1514] Smithsonian Institution. Annals of the Astrophysical Observatory, Volume IV. Washington, D. C., xii + 390 pp. (1922). (Short-period variation of the Sun, pp. 17–18; Variation of spectrum distribution with solar constant, p. 207.)

[1515] Swann, W. F. G. The absence of ionization by electrons with speeds comparable with that of light. Phil. Mag., **47,** 306–319 (1924).

[1516] Taylor, A. H., and L. C. Young. Skip-distance and range table. Radio Engineering Handbook, New York, McGraw-Hill Book Company, Inc., 2d ed., pp. 536–537 (1935).

[1517] Thomson, J. J. Recombination of gaseous ions, the chemical combination of gases, and monomolecular reactions. Phil. Mag., **47,** 337–378 (1924).

[1518] Trowbridge, C. C. On atmospheric currents at very great altitudes. Mon. Weath. Rev., **35,** 390–397 (1907).

[1519] Verman, L. C., S. T. Char, and A. Mohammed. Continuous recording of retardation and intensity of echoes from the ionosphere. Proc. Inst. Radio Eng., **22,** 906–922 (1934).

[1520] Wegener, A. Akustik der Atmosphäre. Müller-Pouillets Lehrbuch der Physik, 11. Aufl., **5,** I, 171–198 (1928).

[1521] Whipple, F. J. W. The investigation of air waves from explosions. Progress in England. Q. J. R. Met. Soc., **57,** 331–335 (1931).

[1522] Wright, A. W. On the polarization of the zodiacal light. Amer. J. Sci. Arts, **7,** 451–459 (1874).

[1523] Young, L. C., and E. O. Hulburt. Radio and sunspot cycle. Phys. Rev., **50,** 45–47 (1936).

INDEX

A

- Abbreviations, 693
- Abnormal *E*-region ionization, 469–474
  - (*See also* Sporadic intense *E*-region ionization)
- Air-earth conduction current, 156, 226
- Air-earth currents, 431–432
  - bibliography, 736
  - determination, direct method, 268
    - indirect method, 269
- Aitken pocket nuclei-counter, 258
  - description, 258
  - operation, 260
- American Geophysical Union, 684
- Anomalies, regional, 425
- Atmosphere, 492
  - (*See also* Upper atmosphere)
- Atmospheric electricity, 149–230
  - conductivity of the atmosphere, 164–210
    - bibliography, 732–736
    - concentration of ions, dependence upon rates of formation, etc., 182–192
      - and nuclei, observed values, 192–197
    - concentration of small ions in free atmosphere, 194–197
    - cosmic radiation, 173–174
    - destruction and transformation of ions, 178–180
    - diurnal variation, 198–200
    - electrical resistance of the atmosphere, 208–210
    - in free atmosphere, 204–208
    - ionizers of the atmosphere, 168–170
    - irregular variations of short duration, 200–201
    - mean life of an ion, 189
    - migration of ions, 180–182
    - mobility of ions, 165–168
    - nuclei in the free atmosphere, 197
    - radioactive matter, 170–173
    - rate of ionization, 174–178
    - at sea, 201–204
    - at the surface, 197–201
  - diffusion, 157
  - electric current in the atmosphere, 226–230
    - conduction-current, 226–227
    - convection-current, 227–229
- Atmospheric electricity, electric current in the atmosphere, supply-current, 229–230
  - electric field of the atmosphere, 210–225
    - electric charge of the air, 220–225
    - general aspects, 211–212
    - potential-gradient, 212–214
    - variations, in gradient at surface, 214–220
      - of potential-gradient types, 215, 216, 217
  - facts established before the end of the 18th century, 152
  - during fair weather, 151, 155
  - general survey, 155–164
  - history, 149–155
  - instruments for, 231–269
  - loose connection with terrestrial magnetism, 385
  - relations to human health, 162–163
  - relations with meteorology, 162
  - relations to other branches of science, 160–162
- Atmospheric tides, 344–345, 349
- Atmospheric-electric instruments, 231–269
  - (*See also* Instruments, atmospheric-electric)
- Atmospheric-electric observatory, 236
- Atmospherics, 394, 395
  - electromagnetic radiation-atmospherics, 672
  - 27-day recurrence, 394
- Attachment of ions, 521
- Audibility, zones of, 499
- Aurora, 46–48, 161, 573–656, 741–744, 768–772
  - bibliography, 741–744, 768–772
  - Brüche's experiments, 409
  - corpuscular theory of, 555
  - data of, 553
  - direction, arcs and bands of, 576
  - direction, streamers of, 574
  - history of, 573
  - magnetic disturbance, relation to and to position of auroral zone, 578, 580, 591, 600, 616
  - motions of, 600
  - radiation-point of streamers of, 575
  - types of, 46–48
    - theoretical explanation of, 598
  - ultraviolet-light theory of, 557

Aurora and the upper atmosphere, 573–656
  auroral spectrum and its interpretation, 616–633
    auroral green line, 580, 616, 620, 641, 652
    auroral lines observed and measured spectrographically, 619–624
    historical remarks, 616–619
    intensity distribution within spectrum, 632–633
    interpretation of auroral spectrum, 624–632
    production in laboratory, 558
  auroral spectrum and upper atmosphere, 641–656
    composition of upper atmosphere, 641–642
    electrical state of upper atmosphere and terrestrial corona, 647–654
    upper limit of temperature of auroral region, 642–647
    zodiacal light, solar corona, and comets' tails, 654–656
  electric rays, their properties, origin, and constitution in relation to theory of aurorae and magnetic disturbance, 601–616
    absorption in atmosphere, 601–603
    consequences to be inferred from distribution of luminescence, 605–610
    relation between aurora and magnetic disturbances and position of auroral zone, 613–616
    source of, 610–613
    theoretical distribution of light-intensity, 603–605
  intensity-variations within auroral spectrum, 633–641
    altitude-effects, 636–638
    interpretation of spectral variations, 639–641
    spectral changes producing red auroras, 633–636
    variation of spectrum with type of aurora, 638–639
  introductory account, 573
  space-time distribution of aurora and solar and terrestrial relationships, 574–588
    annual period, 581
    correlation of aurora and solar activity, 581–582, 634, 635
    direction of arcs and bands, 576–578
    direction of streamers, 574–576
    distribution of light-intensity along streamers, 587–588
    diurnal distribution of frequency, 579–581, 615
Aurora and the upper atmosphere, space-time distribution of aurora and solar and terrestrial relationships, geographical distribution of frequency, 578–579
    height of, 582
    lower limit, 584–585
    position in space, 582–584
    relation between motion and intensity, 580
    times of evening maximum, 580
    typical forms, 574; quiet, 574; moving, 574
    upper limit, 585–587
  theory, 588–601
    Birkeland's theory, 590–592
    Birkeland's work on magnetic disturbances, 592–594
    electric rays produced in Earth's atmosphere by solar radiation, 589–590
    general considerations, 588–589
    motions of aurora, 600–601
    Störmer's mathematical theory, 594–598
    theoretical explanation of auroral forms, 598–600
Automatic controls, 238, 245, 248, 252, 258, 263
  conductivity hourly-zero condenser, 245
  program-machines, 238, 263

B

Barlow, evidence that natural electric currents flow in Earth's crust, 271
Berlin, earth-current measurements, 271, 285, 294, 295, 302, 303, 305, 306
Bibliographical notes and selected references, 679–778
  American Geophysical Union, 684
  bibliographies and abstracts, 692–778
    abbreviations, 693
    classification of bibliography, 680–681
    cosmic radiation, 758–763
    geophysical prospecting, 747–749, 772–774
      electric methods, 748–749
      general, 747–748
      magnetic methods, 748
    ionosphere, 749–758, 774–778
    miscellaneous, 765–778
      aurora, 768–772
      earth-currents, 772–778
      geophysical prospecting, 772–774
      ionosphere and upper atmosphere, 774
      terrestrial electricity, 766–768
      terrestrial magnetism, 765–766
    terrestrial electricity, 724–746, 766–768
      air-earth current, 736

Bibliographical notes and selected references,
      bibliographies and abstracts, terrestrial electricity, aurora, 741–744, 768–772
    conductivity, ion-mobility, etc., 732–736
    earth-currents, 744–746, 772–778
    electricity of precipitation, 736–738
    general, 724
      handbook articles, theoretical and descriptive papers, 724–726
      observations, 726–728
    instruments and methods of measurement, 728–730
    potential-gradient and space-charge, 730–732
    thunder-storms and lightning, 738–740
  terrestrial magnetism, 693–724, 765–766
    expeditions, 699–701
    general, 695
      classical and reference works, 695–698
      solar magnetism, 698–699
    history, 693–695
    instruments, 701
      comparisons of, 706
      and methods of measurement, 701–705
    international bodies, 681–684
    International Association (formerly Section) of Terrestrial Magnetism and Electricity, 682
    International Astronomical Union, 683
    International Commission for Terrestrial Magnetism and Atmospheric Electricity, 683
    International Council of Scientific Unions, 683
    International Meteorological Committee, 682–683
    International Meterological Organization, 682
    International Research Council, 683
    International Union of Geodesy and Geophysics, 682
    introductory remarks, 679–680
    magnetic anomalies, 722–724
      local, 722–723
      magnetism of rocks, etc., 723–724
    magnetic disturbances, pulsations, solar, and cosmical relations, 717–722
    periodic variations (diurnal, lunar, annual, etc.) and magnetic activity, 712–716
    permanent field, 706–712
      general, 706–708

Bibliographical notes and selected references,
        introductory remarks, permanent field, magnetic surveys, charts, and tables, 708–711
      observatories, 711–712
    popular addresses and essays of non-technical content, 701
    secular variation, 716–717
    works pertaining to the history of, 693–695
  ozone, 764–765
  publications of observatories and institutions, 684–689
  radioactivity, 763–764
  scientific journals and memoirs, 689–692
Bache magnetometer, 67
Bibliography, classification of, 680–681
Boys camera, 677
Breit and Tuve radio-echo method, 502
British Association for the Advancement of Science, 681–682
Bronson high-resistance radioactive cell, 246, 257

C

Carnegie, 20, 21, 161, 168, 169, 176, 193, 202, 211, 215, 226, 319
Carnegie Institution of Washington, 20, 22, 30, 40, 49, 57, 69, 72
  Researches, Department of Terrestrial Magnetism, 685
Cathode-ray oscillograph in study of field-changes, 658
Charged clouds, interaction with ionosphere, 671
Chesterfield Inlet, 272, 284, 285, 293, 295
Coefficients, atmospheric-electric, 178–180, 185, 197
  of attachment, 179
  of combination, 179
  of recombination, 178
    dependence on pressure and temperature 180, 197
  relation between, 185
Collectors, 151
College-Fairbanks, Alaska, earth-current measurements, 272, 276, 281, 284, 293 299
Comets, 563
Comets' tails, 656
Compass, 64, 75, 76, 93, 96
  -declinometer, 93
  -deflector, 76
  history of, 64

- Compass, marine collimating-, 75
  - ship's compass, 96
  - -variometer, 95
    - (*See also* Instruments, magnetic)
- Conductivity, 533
  - ion-mobility, etc., bibliography, 732
- Conductivity-apparatus, Gerdien, 242
  - modified observatory recorder, 248
  - observatory records, 243
  - portable field-type, 242
  - stratosphere recorder, 250
  - theory of, 245
    - (*See also* Instruments, atmospheric-electric)
- Conductivity-calibration apparatus, 246, 249
  - variable condenser, 249
  - variable potentiometer, 246
- Conductivity-cylindrical condenser, 242, 244, 250
  - electrical capacity of, 245
  - potentials on, 244
  - rate of air-flow through, 242, 245
- Corpuscles from Sun, 382, 404
  - electrically neutral, 408
  - Störmer's theory, 405
- Corpuscular theory, 404
  - of aurora, 555
  - of magnetic storms, 554
- Cosmic radiation, 173
  - bibliography, 758–763
  - discovery of, 161, 173
  - effect of electrified particles on, 674
  - intensity of, indicative of rate of ionization, 176
  - as an ion-forming agency, 161, 168, 177
  - variation with altitude, 174
  - variation with magnetic latitude, 173
- Coulomb's law, 154
- Critical frequency, 504
- Critical wave-length, defined, 502
- Curie (unit), 171
- Currents in Earth, 270
  - affecting secular variation, 332
  - as cause of permanent field, 322
  - induction of, 356
    - (*See also* Earth-currents)
- Current-systems, 355
  - of bays, 371
  - determination of heights of, 365, 373
  - of diurnal variations, 348, 353
  - of magnetic storms, 364, 369, 403
  - of solar-flare disturbances, 380
    - (*See also* Earth's magnetism; Terrestrial magnetism)

D

- Davy, Sir Humphrey, existence of earth-currents, 270
- Deflector for measuring magnetic horizontal intensity at sea, 76
- Diamagnetic theory, solar diurnal variation, 412, 428, 541
- Diamagnetism, 535
  - of the high atmosphere, 324, 349
- Diffusion in the upper atmosphere, 493
- Diffusion-levels of atmospheric gases, 493
- Dip-circle, 60, 63
  - Dover land-type, 65
  - first, 64
  - Lloyd-Creak sea-type, 77
- Dispersion in the ionosphere, 444
  - near critical frequencies, 490
  - leading to distortion, 490
- Distribution-coefficients (*P* and *Q*), 100
- Diurnal variations
  - of atmospheric electricity, 151, 155
    - discovery, 150
  - of ionosphere, 457, 508
    - absorption, 466
    - E- and F_1-regions, 453
    - F_2-regions, 458
  - of terrestrial magnetism, lunar, 341, 545
      - changes with lunar distance, 342
      - comparisons with solar, 342
      - spherical harmonic analysis, 343
    - solar, 334, 536
      - augmented by solar flares, 381
      - changes in, 335, 338, 354
      - geographical distribution, 337
      - internal and external components, 340
      - spherical harmonic analysis, 339
      - in Western Hemisphere, 341, 352
  - theories, 344
    - comparison of, 351
- Dolezalek quadrant-electrometer, 235, 244, 267
  - (*See also* Electrometers)
- Drift of ions, 534
  - electric drift, 534
  - gravitational magnetic drift, 535
- Drift-current theory, solar diurnal variation, 412, 542
- Drift-currents in high atmosphere, 324, 349
- Dynamo-effect, 535
- Dynamo-theory, of lunar variation, 546–547
  - of solar diurnal variation, 411, 537

E

- Earth-currents, 270–307
  - activity, relation with solar activity, 302

- Earth-currents, activity, seasonal changes, 299
  - bibliography, 744–746, 772
  - definition of, 270
  - disturbances, 290–293
    - connection with magnetic storms and aurorae, 271, 290
    - connection with sunspot-frequency, 271
    - 27-day recurrence, 291
  - general circulation, in equatorial regions, 298
    - in polar regions, 297
  - historical, 270–272
  - introductory account, 270
  - measurements, 272–289
    - data required, 272
    - effect contact-potentials at electrodes, 277, 289
    - electrodes, 274–279
    - general, 272–273
    - lines, 283–286
      - arrangement of electrodes, 284
      - duplicate installations, 285
      - insulation-requirements, 283
      - length of, 284
      - orientation of, 273, 284
      - overhead and underground, 283
  - of potential, 272
  - present status of investigation, 306–307
  - recording instruments, 279–283
  - relation to magnetic variations, 302–306
    - theory of, 306
  - resistivity, 286–288
    - in geophysical prospecting, 288–289
  - results of observations, 289–302
    - constant or unidirectional, 289–290
    - disturbances and storms, 290–293
    - periodic changes, 293–302
      - at College-Fairbanks, 296
      - at Huancayo, 293
      - at middle-latitude stations, 303
  - vertical, 290, 430
- Earth-inductor, 60, 70, 77
  - land type, 60, 70
  - sea type, 77
- Earth's interior, 320
- Earth's magnetic field, separation of interior and exterior parts, 399
- Earth's magnetism and its changes, causes of, 308–384
  - harmonic functions, 309–314
    - application of harmonic analysis to Earth's magnetic field, 311
    - internal, external, and non-potential fields, resolution of, 312–314
  - induction of electric currents within Earth, 355–359
- Earth's magnetism and its changes, introductory account, 308–309
  - magnetic disturbances, 359–384
    - after-field and non-cyclic change, 379
    - bays, 370–375
    - diurnal variation on disturbed days, 365–370
    - pulsations, 381–382
    - solar-flare disturbance, 379–381
    - storm-time variations, 360–365
    - sudden commencements, 376–378
    - theories, 382–384
  - permanent field, 314
    - external and non-potential fields, 317–318
    - general description, 314–317
    - reality of internal, external, and non-potential fields, 318–320
    - theories of external and non-potential fields, 324–325
    - theories of internal field, 320–324
  - secular variation, 325–334
    - changes, in external field, 331–332
      - in magnetic moment of Earth, 325–327
    - local effects, foci, 328–331
    - revolution of magnetic poles, 327
    - theories to explain, 332–334
  - solar and lunar diurnal variations, 334–355
    - comparison of theories, 351–355
    - geographical distribution, 337–339
    - lunar diurnal variation, 341–334
    - solar diurnal variation in low and middle latitudes, 334–337
    - spherical harmonic analyses, 339–341
    - theory, 344–351
- Earth's magnetism and magnetic surveys, 1–58
  - anomalies, 28–33
  - early history, 1–3
  - Earth's magnetic field, 3–5
  - irregular variations and magnetic activity, 42–49
  - lunar and annual variations, 39–42
  - magnetic surveys, 13–24
  - secular variation, 7–13
  - secular-variation foci, 24–27
  - solar activity, 49–53
  - solar diurnal variation, 33–39
  - time-changes, 5–7
- Earth's negative charge, 156, 163, 229
- Ebro Observatory, earth-current series, 272, 282, 284, 285, 286, 287, 289, 292, 294, 295, 302, 303, 304, 305, 306
- Eclipse of Sun, decrease of ionization during, 454
  - effects in F_2-region, 462
- Electric charge on rain, 661, 666

Electric conductivity, of Earth, 322, 358
  of high atmosphere, 309, 346, 352
    changes in, 355
Electric current, in the atmosphere, 226
    conduction-current, 226
      diurnal variation, 226
    convection-current, 227
    supply-current, 229
  flowing up mountain sides, 160
Electric field of the atmosphere, 210
  general aspects, 211
  potential-gradient in free atmosphere, 212
  variations of gradient at surface, 214
Electric fields, breakdown field in presence of drops, 661
  discharge field-changes, 659
  at Earth's surface, 657
  fine-structure of field-changes, 660
  polarity of lightning-strokes to elevated conductors, 660
  sign and value of, 659
Electric rays, relation to theory of aurorae and magnetic disturbances, 601
    neutral streams, 612
  sign, 578, 611
  source, 610
Electrical conductivity of the air, 164
  discovered, 151
  at sea, 201
    in the free atmosphere, 204
    registrations on the *Carnegie*, 202
    results, stratosphere flight, *Explorer II*, 177, 180, 204
  at the surface on land, 197
    annual variation, 198
    diurnal variation, 198, 202
      at Huancayo and Watheroo observatories, 199
    irregular variations of short duration, 200
Electrical dissipation, 154
Electrical resistance of the atmosphere, 208
Electrically neutral streams of solar particles, 408
Electricity of precipitation, bibliography, 736–738
Electrode-effect, 185
Electrodes, 271, 274
  contact-potentials of, 276, 277
  contact-resistance of, 276
  installation, 276
  insulation of, 278
  metallic, 274
  requirements, 274
  reversible, 274
Electrodynamics of the upper atmosphere, 531
Electromagnetic magnetometer, 63–64, 71
Electrometers, capillary, 240
  Dolazalek quadrant, 235, 244, 267
  Lutz unifilar, 243, 248, 250, 253
  Wulf bifilar, 234, 243
  Wulf unifilar, 243, 249, 263, 265
Electromotive forces in the atmosphere, 345, 353, 381
Electron-density in ionosphere, 451
  calculation of, 445
  relation to ion-density, 448
    (*See also* Ion-density.)
Energy-density of magnetic storms, 550
E-region, 443, 501, 506
  diurnal variation, 453, 454
  height, 451
  importance to radio transmission, 486, 489
  ion-density, 443, 451
  ionizing radiation responsible for, 457
  during magnetic disturbances, 472, 478
  at night, 455
  seasonal variation, 455
  theory of, 524
  thickness of, 471
  variations, 506
    during solar eclipse, 456
    with sunspot-number, 455, 457, 464
  virtual heights, 506
Experiments with magnetized spheres, 591, 598
Explorer II, 177, 180, 202, 204, 209, 250

F

Fade-out (*see* Radio fade-out)
Fade-out disturbances, 614, 654
Faraday, unsuccessful attempts to detect earth-currents, 271
Franklin, Benjamin, experiments on lightning, 149, 657
Franklinian theory of electricity, 149
F-region, 453, 509
  importance of radio transmission, 486, 489
  during magnetic storms, 476, 479
  separation into F_1- and F_2-regions, 451, 453
F_1-region, 451, 525
  diurnal variation, 453
  height, 451
  importance in radio transmission, 489
  ionizing radiation responsible for, 457
  during magnetic storm, 474
  seasonal variation, 455
  separation from F-region, 451
  variation, during eclipse, 456
    with sunspot-numbers, 455, 457, 464
F_2-region, 451, 495, 501, 526
  anomalous effects, 457, 461

F_2-region, anomalous effects, indicated by solar changes, 464
  bite-out effect, 462
  diurnal variation, 458
  height, 452
    variations of, 458
  importance in radio transmission, 486, 489
  ionizing forces responsible for, 462
  non-seasonal change, 459
  noon-average, 460
  seasonal variation, 458
  separation from F-region, 451
  theory of, 526
  variation, during eclipse, 462
    with sunspot-number, 435, 463
Fritz, H., map of auroral frequency, 578

G

Galilee, 21, 319
Galvanometers, D'Arsonval-type, 280
    advantages of, 281
  limit of resistance, 282
  for recording earth-potentials, 280
  recording circuit for use with, 281
  sensitivity, 282
Gauss, C. F., 16, 23
  analysis of Earth's magnetic field, 439
Gauss, unit of magnetic intensity, 111
Gegenschein, 564
  atmospheric theory of, 567
  planet-dust theory of, 566
Geophysical prospecting
  bibliography, 747–749, 772–774
  electric, 748
  general, 747
  magnetic, 748
  resistivity, 288
    (*See also* Magnetic prospecting)
Gimbal, reversible for ship use, 77, 80
Greenwich, earth-current measurements, 271 285, 294, 302

H

Halley, Edmund, 8, 9, 18
  isomagnetic chart, 8
Hogg's ionization-apparatus, 263
  description, 263
  operation, 264
Hotchkiss superdip, 127
Huancayo Magnetic Observatory, 22, 23
  design of, 89, 90
  diurnal variation at, 36, 41
  earth-current measurements at, 272, 276, 279, 283, 289, 291, 292, 294, 299, 302, 304, 306
Huancayo Magnetic Observatory, location with respect to atmospheric-electric observations, 199

I

Induction-coefficient, determination of, 101
Induction-variometer, 84
Instrumental constants and standardizations, 98–103
  declination, 98
  horizontal intensity, 99–102
  inclination, 98
Instruments, atmospheric electric, 231–269
  air-earth current, 268–269
  auxiliary, 269
  conductivity, 241–252
  introductory account, 231–232
  ion-counters, 252–258
  ionization-apparatus, 262–267
  nuclei-counters, 258–262
  potential-gradient, 233–241
  space-charge, 267–268
Instruments, ion-counting, 252
  auxiliary cylindrical condenser, 255
    electrical capacity of, 254
    potentials of, 253
    rate of air-flow through, 252
  general description, 252
  intermediate ion, 253
  large ion, 254
  small ion, 253
Instruments, ionization, 262
  general description, 262
  cosmic-ray meters, 263
  Hogg's apparatus, 263
  Wait's apparatus, 264
Instruments, magnetic, 59–109
  early history, 64–66
  instrumental requirements, 59–64
    declination, 59
    inclination, 60–61
    intensity, 61–64
  practice at magnetic observatories, 103–109
  types of instruments, 66–103
    absolute, 66–78
      for land, 66–75
      for sea, 75–78
    to determine periodic and irregular variations, 79–93
      equipment for housing apparatus, 88–93
      for use at observatories, 79–88
    special instruments and equipment, 93–98

Instruments, magnetic prospecting, 118
  classification and general theory, 118
  Hotchkiss superdip, 127
  magnetic theodolites and observatory instruments, 131
  other prospecting instruments, 129
  Schmidt horizontal balance, 124
  Schmidt vertical balance, 112, 120
Interchange of electricity between electrified clouds and the Earth, 670
  by ionic conduction, 671
  by lightning, 671
  by rain, 671
Intermediate-ion counter (*see* Ion-counting instruments)
International Association of Terrestrial Magnetism and Electricity, 682
International Astronomical Union, 683
International bodies, 681
International Commission for Terrestrial Magnetism and Atmospheric Electricity, 682, 684
International Council to further the Study of Solar and Terrestrial Relationships, 683
International Council of Scientific Unions, 683
International magnetic standard, 70
International Meteorological Organization, 682, 684
International Polar Year 1932–33, earth-current measurements, 272, 276, 284, 292, 299
International Union of Geodesy and Geophysics, 682
Ion-density, 182, 434, 653
  concentration small ions in the free atmosphere, 194
  in ionosphere, abnormal *E*-region, 469
    change during fade-out, 464
    computation, 444
    correlation with sunspot-numbers, 456, 463
    determination, 442, 445
    distribution, 451
    diurnal variation, 453, 458
    E- and F_1-regions, 453
    F_2-region, 458, 459, 463
    during magnetic storms, 474
    seasonal change, 455, 458
    source producing, 434, 457, 462, 469
    in troposphere, 482
    variation with sunspot-numbers, 435, 455, 460, 463
  layers of, 653
  relations between ion-forming and ion-destroying processes, 182
Ionization, coincidence with auroral activity, 471
  coincidence with magnetic disturbance, 471
  curves of, 517
  distribution in ionosphere, 443, 451
  of outer atmosphere, 434
  sporadic in *E*-region, 469
  variation, with altitude, 176, 177
    in place and time, 175
    (*See also* Atmospheric electricity)
Ionized regions, of the atmosphere, rôle in radio transmission, 483
    (*See also* Ion-density; Ionization)
  of the high atmosphere, 501
Ionizers of the atmosphere, 168
  breakers along sea-shore, 169
  combustion, 169
  cosmic radiation, 168, 170
  drifting dust or snow, 169
  electrical discharges, 169
  ionization by collision, 168
  radioactive matter, 168, 170, 171
  ultraviolet light from Sun, 168, 169
Ionosphere, 162, 180, 514, 749, 774
  anticipated from observations of Earth's magnetism, 386
  Balfour Stewart's theory, 439
  bibliography, 749–758, 774–778
  critical frequency, 444
  double refraction in, 446
  D-region, 469
  E- and F_1-regions, 454
  evidence of, 440
  F_2-region, 457
  general nature of, 450
  heights, 451
  interaction of charged clouds with, 671
  proof of reality of, 441
  radio exploration of, 434
  reflections of short retardation from, 482
  relation with sunspot-cycle, 513
  scattered reflections from, 481
  seasonal change, 452, 455, 460
  during a solar eclipse, 512
  sources of knowledge regarding, 387
  theory of, 514
    E-region, 524
    F_2-region, 526
    ionization-curves, 517
    ultraviolet light of Sun, 514
  virtual height, 434, 440, 445
Ionospheric data, 450
Ionospheric investigation automatic multifrequency, 448
  Breit-Tuve experiment, 441
  multifrequency method, 442

Ionospheric investigation, technique, 434
Ionospheric records, during abnormal *E*-region, 470
  determination of propagation-conditions from, 486, 489
  during fade-out, 465
  interpretation of, 443
  magnetically disturbed, 473, 476, 479
  seasonal characteristics, 452
  typical, 450
Ions, 155
  attachment, 521
  concentration of, 182
    observed values, 192
  destruction and transformation of, 178
  large or Langevin, 167
  life of, 189
  migration of, 180
    by eddy-diffusion, 181
    by electric field, 181
    by wind, 180
  mobility of, 164, 165
  motions in crossed fields, 534
  over mountain peaks, 155
  recombination of, 518
  small, 165, 178
Isoceraunics, 674
Isomagnetic charts, 10
  Halley's, 10
  isoporic, 24, 25, 27
  United States Hydrographic Office, 11
Isopors, 24–27

K

Kennelly-Heaviside layer, 439
  (*See also* Ionosphere)
Kursk anomaly, 112

L

Large-ion counter, calibration-apparatus, 258
  (*See also* Instruments, ion-counting)
Lightning, bibliography, 738–740
  branching of and criterion of, 666
  component strokes of discharge, 675
  development of discharge, 677
  electrical effect of direct strokes, 675
  energy, and current in discharge, 664
    spent in producing, 664
  photographs of, 675
  protection against, 162
  rods, 149, 150, 162
  time-variation of current in discharge, 676
Luminescence, consequences to be drawn from distribution of, 605
Luminous night clouds, 641, 642, 647
Lunar diurnal variation, 39, 50, 413, 545
Lutz unifilar electrometer, 243, 248, 250, 253
  (*See also* Electrometers)

M

Magnetic activity, 42
  bibliography, 712
  relation with solar activity, 49
  and sunspot-numbers, 437
Magnetic anomalies, 28, 112, 317, 321
  bibliography, 722
Magnetic bays, 370
Magnetic character-figures, 42
Magnetic character-numbers, 388
  reliability of, as an index for solar action in the Earth, 393
Magnetic charts, Carnegie Institution world survey, 19
  Halley's declination, 10
  isoporic declination for United States, 25
  isoporic declination for world, 24
  United States Hydrographic Office, 12
    isoclinic, 12
    isodynamic, 13
    isogonic, 12
Magnetic disturbances, association with abnormal *E*-region, 472, 481
  auroral relations, 47
  auroral-zone relations, 613
  bibliography, 717
  Birkeland's theory of, 590
  Birkeland's work on, 592
  coincidence with ionospheric effects, 474
  electric current-system, 593, 600, 614, 615
  giant pulsations, 48
  micropulsations, 48
  seasonal variations of associated ionospheric effects, 478
Magnetic elements defined, 59
  declination, 59
  inclination, 60–61
  intensity, 61–62
Magnetic field of the Earth, 3, 314
  magnetic poles, 3
  permanent, 314
    approximate representations, 316
    external, 317
    internal, 314
    line-integrals of, 319
    non-potential, 318
    origin, 320
    reality of components, 318
  time-changes, 5
    (*See also* Terrestrial magnetism)

Magnetic field of the Sun, 322
Magnetic fluctuations, 429
    (*See also* Magnetic storms)
Magnetic instruments, absolute, 66
    for use on land, 66
      at sea, 75
  bibliography, 701
    comparisons of, 706
  history, 64
  special, 93
    compass-declinometer, 93
    compass-variometer, 95
    miscellaneous, 97
    quartz-fiber horizontal magnetometer (QHM), 94
    ship's compass, binnacle, and azimuth-circle, 96
    transit-magnetometer, 94
  variation-instruments for observatories, 79
    declination, 80
    horizontal intensity, 81
    induction, 84
    la Cour, 86
    Schmidt, 85
    vertical intensity, 82
    (*See also* Instruments, magnetic)
Magnetic intensity, 61
  determination, 62
    by electromagnetic methods, 63
    by magnetic methods, 63
  first measurements, 66
Magnetic international standard, 70
Magnetic observatories, 22, 88–92, 103–109
  bibliography, 711
  distribution, 21, 22
  portable, 109
  practice at, 103–109
Magnetic permeability, 113, 114
Magnetic phenomena, conventional subdivision of, 400
Magnetic properties of rocks, definitions, 113
  factors determining rock-magnetization, 117
  methods of determination, 114
  numerical data, 116
Magnetic prospecting, 110–148
  applications, 112–113
  corrections, 131–134
    base-correction, 132
    iron objects, 132
    magnetic variations, 132
    normal values, 134
    planetary effects, 132
    temperature, 131
    terrain-effects, 133
  general features, 110–111
Magnetic prospecting, historical development, 111–112
  magnetic instruments, 118–131
    classification, general theory, 118–120
    Hotchkiss superdip, 127–129
    miscellaneous, 129–131
    Schmidt balances, 120–127
      horizontal, 124–127
      vertical, 120–124
    theodolites and observatory instruments, 131
  magnetic properties of rocks, 113–118
    definitions, 113–114
    factors determining, 117
    methods for determining, 114–116
    numerical data, 116–117
  magnetic surveys, results of, 143–148
      in civil engineering, 146–148
      in mining exploration, 143–145
      in oil exploration, 146
  theory of interpretation, 134–143
    graphical representation, 135–136
      disturbance-vectors, 136
      isanomalic lines, 135
      magnetic gradients, 136
      profiles at right-angles to strike, 136
    model-experiments, 142
    pole- and line-theory, 136–139
    relation to anomalies, 139–141
    torsion-balance diagrams, use of, 141–142
    underground and aerial surveys, 142–143
Magnetic storms, 359, 401
  average magnetic storm, 401
  corpuscular theories of, 554
  data of, 547
  diurnal variation on disturbed days, 365
  equivalent current-system, 403
    relation, with radio, ionosphere, and Sun, 551
    to Sun, 382
  Störmer's theory, 405
  storm-time variation, 360
  sudden commencements, 401
  theories of, 382
  ultraviolet-light theory of, 559
Magnetic surveys, 13
  bibliography, 708
  land, 20
  sea, 8, 18
  world magnetic survey of Carnegie Institution of Washington 1905–38 (map), 19
Magnetic tabulations, form of, 107
Magnetic zenith, coincidence with radiation-point of auroral crown, 575
Magnetism of rocks, bibliography, 723

Magnetization of rocks, 326
Magnetograph, la Cour, 86
Magnetometers, Bache, 66
  Carnegie Institution of Washington, 68
  coil of electromagnetic, Carnegie Institution of Washington, 72
    Dye, 74
    Schuster-Smith, 71
    Watson, 71
  electromagnetic, 71
  Kew, 67
  magnetometer-inductor, 69
  QHM, quartz-fiber horizontal, 94
Marine collimating-compass, 75
Mean life, of large ions, 190
  of small ions, 189, 196
Meteor-trains, 498
Micropulsations, 430
"Mobile conductor" of De Saussure, 152
Molecular densities, of the atmosphere, 497
  of the gases of the atmosphere, 496
Mont Pelée eruption 1902, 45
M-regions on Sun, 390

N

Nitrogen, band-spectra of, 624, 626, 641, 652
Non-cyclic change, 379
Non-magnetic material for instruments, 102–103
Nuclear-physics research pertaining to magnetism, 55
Nuclei in the free atmosphere, 197
Nuclei-counting instruments, 258
  Aitken pocket counter, 258
  Owens automatic pollution-filter, 262
  Owens jet dust-counter, 262

O

Observational data, on land, 428
  need for, 428
  at sea, 429
Observatories and institutions, publications of, 684
Observatory, atmospheric-electric, 236
Observatory results, utilization of, 416
Owens automatic pollution-filter, 262
Owens jet dust-counter, 262
Oxygen, lines of, 627
Ozone, 568, 632, 641, 764
  bibliography, 764
  distribution of, 568
  in lower atmosphere, 570
  theories regarding, 572
  in upper atmosphere, 494
Ozone, variations of, 569
  vertical distribution of, 571

P

Parc St. Maur, Paris, earth-current measurements, 271
Pedersen ray, 488
Periodic variations of Earth's magnetism, bibliography, 712
Permanent magnetic field of the Earth, 421
  bibliography, 706
  hypotheses on origin of, 424
    (*See also* Earth's magnetism; Terrestrial magnetism)
Point-discharge apparatus of Whipple and Scrase, 658
Poisson's theorem, 224
Polarization in ionosphere, 446
Potential analysis, 309
  application to Earth's magnetic field, 311, 339, 343, 375
  theory and procedure, 309, 373
Potential-gradient and space-charge, bibliography, 730–732
Potential-gradient apparatus, description, 234
  field "stretched-wire," 234
  insulation, 234–239
    (*See also* Instruments, atmospheric-electric)
  null or compensating, 239
  observatory recorder, 235
Potential-gradient collector, elevated point, 240
  elevated sphere, 240
  for fair weather, 233
  mechanical, 233
  radioactive, 233
  for stormy weather, 240
  test-plate, 240
Potential-gradient observations, on balloon flights, 153
  inaugurated at Kew Observatory, 152
  at other places, 153
Potentiometers for measuring earth-potentials, 279
  advantages, 279
Primary standard, all elements, 74
Problems of terrestrial magnetism and electricity, 385–433
  earth-currents and air-earth currents, 430–433
    air-earth currents, 431–432
    terrestrial magnetism and earth-currents, 432–433
    vertical earth-currents, 430

- Problems of terrestrial magnetism and electricity, general features of a magnetic field, 399–401
    - separation of interior and exterior parts, 399–400
    - subdivision of magnetic phenomena, 400–401
  - introductory account, 385–386
  - ionosphere, relations to, 386–387
    - anticipated from terrestrial-magnetic observations, 386–387
    - sources of knowledge of, 387
  - magnetic activity and the Sun, 387–399
    - characterization, 387–388
    - coordination of phenomena, 393
    - diurnal variation, 398–399
    - magnetic character-figure as index for solar action in the Earth, 393–394
    - recurrence-tendency as model of quasi-persistence, 395
    - seasonal variation, 397–398
    - sun's M-regions, 390–393
    - 27-day recurrence-tendency, 388–390
    - 27-day recurrence-tendency in other phenomena, 394–395
    - u-measure, 395–397
  - magnetic fluctuations between 10,000 and one cycle per second, 429–430
  - magnetic storms, 401–409
    - average magnetic storm, 401–403
    - electrically neutral streams of solar particles, 408–409
    - equivalent current-system, 403–404
    - solar streams of corpuscles, 404–405
    - Störmer's theory, 405–407
    - theories, additional, 409
  - permanent field and secular variation, 421–429
    - anomalies, regional, 425
    - hypothesis on origin of main part, 424–425
    - interior field, main part of, 422–424
    - need of new observational material, 428–429
    - observations at sea, 429
    - permanent field, 421–422
    - secular variation, 425–428
  - solar and lunar diurnal variations, 409–421
    - lunar diurnal variation, 413–416
    - solar diurnal variation, observations of, 409–411
      - theories of, 411–412
    - statistical methods for research on variability, 418–421
    - utilization of observatory-results, 416–417
- Problems of terrestrial magnetism and electricity, solar and lunar diurnal variations, variability of solar diurnal variation, 417–418
- Pulsations, 381

Q

- Quantum-theory of temperature of auroral region from band-spectra, 642, 643
- Quasi-persistence, 395

R

- Radio exploration of Earth's outer atmosphere, 434–491
  - automatic multifrequency methods, 448–450
  - Breit-Tuve experiment, 441–442
  - double refraction in ionosphere, 446–448
  - E- and F_1-regions, 454–457
  - F_2-region, 457–464
  - general nature of ionosphere, 450–454
  - historical background, 439–440
  - introductory account, 434–438
  - ionospheric effects coinciding with magnetic storms, 474–481
  - multifrequency method, 442–446
  - radio fade-outs, 464–469
  - reflections of short retardation, 482–483
  - rôle of ionized regions in radio transmission, 483–491
  - scattered reflections, 481
  - sporadic intense E-region ionization, 469–474
- Radio fade-out, 50, 435, 464
  - associated with bright chromospheric eruptions, 464
  - examples of, 465
  - first announcements, 464
  - ionizing radiation producing, 468
  - magnetic effect, 435, 465, 469
  - relation to diurnal variation of geomagnetism, 469
- Radio transmission, calculation of propagation-conditions of, 483, 487
  - dispersion and distortion, 490
  - effect of curved Earth on, 484, 487
  - effect of ionosphere in, 483
  - importance of ionospheric regions to, 483, 486, 489
  - multiple transmission, 489
  - Pedersen ray, 488
  - skip-distance, 488
  - use of records to determine, 485, 488
  - over very short distances, 484

Radioactive matter, in the atmosphere, 161, 171
  content of rocks, 170
  distribution with altitude, 172
  in freshly fallen rain or snow, 172
  of sea-water, 170, 172
Radioactivity, bibliography, 763
Recombination-coefficient, 178–180
  dependence upon pressure, 180
  dependence upon temperature, 180
Recombination of ions, 518
Refraction of radio waves, 444
  double, 446
  at oblique incidence, 446, 483, 487
Research, 21
Resistivity of ground, earth-resistivity meter, 286
  laboratory measurements, 286
  resistivity of earth-materials, 288
  resistivity-data at sites of earth-potential measurements, 287, 295
  use of resistivity data to determine concealed structure, 288, 289
Results of earth-current measurements, 289

S

Scaling-glass for magnetograms, 105
Schmidt horizontal balance, 124
Schmidt vertical balance, 112, 120
Scientific journals and memoirs, 689
Seasonal changes in earth-current activity, 299
  parallelism with magnetic seasonal changes, 302
Secular variation, 5, 7, 32, 53, 325, 425, 716
  bibliography, 716
  causes of, 332
  external field, 331
  geomagnetic constant, 331
  local effects (foci), 328
  of magnetic poles, 327
  of total magnetic moment of Earth, 325
Sine-galvanometer, 72
Skip-distances of radio waves, 488, 528
Small-ion counter (*see* Instruments, ion-counting)
Sodankylä, Finland, earth-current measurements, 272
Solar activity, correlation with aurorae, 581
Solar corona, 654
Solar diurnal variation, 33, 50, 409
  observations of, 409
  theories of, 411
  variability of, 417
    investigation of, by statistical methods, 418
Solar eclipse, effect on the ionosphere, 454, 462, 512
Solar electric rays, absorption in the atmosphere, 601
  air-equivalents, 609
  light-pressure, 612, 656
Solar eruptions, of April 6, 1936, 436
  beam- and flare-theories of, 562
  coincidence of fade-outs with, 435, 455
  of July 31, 1937, 466
  of September 1, 1859, 464
Solar streams of corpuscles, 404
Solar-flare disturbances, 379
  relation with magnetic storms, 384
  relations with diurnal variations, 381
Sound-waves, propagation through the atmosphere, 499
Space-charge, bibliography, 730–732
  variation with altitude, 224
    major aspects of, 225
  variation with time, 220
Space-charge apparatus of Brown, 267
Spectrographs, 617
Spectrohelioscopic observations, 394
Sporadic intense E-region ionization, 469
  cause of, 474
  distribution with latitude, 471
  height of, 471
  record of, 470
  relation to magnetic disturbance, 471
Stenquist, D., earth-current measurements in Sweden, 272
Stewart-Schuster atmospheric dynamo-theory, 411
Störmer, C., mathematical theory of aurora, 594
  theory of solar particles, 405
Stratosphere, 492
Sudden commencements, 360, 376, 547
Sun-dials, Nüremburg, 65
Sunspot-cycle, relation with the ionosphere, 513
Sunspot-number, relation of ionosphere to, 434, 455, 463
    (*See also* E-region; F_1-region; and F_2-region)

T

Temperature, of the auroral region, 642
  of the upper atmosphere, 494, 501
Temperature-coefficient of magnets, 100
Tent for magnetic observations, 92
"Terrella" of Birkeland, 405
Terrestrial electricity, bibliography, 724–746, 766–768

Terrestrial electricity, bibliography, air-earth current, 736
    aurora, 741–744, 768–772
    conductivity, ion-mobility, etc., 732–736
    earth-currents, 744–746, 772–778
    electricity of precipitation, 736–738
    general, 724
    instruments and methods of measurement, 728–730
    miscellaneous, 766–768
    observations, 726–728
    potential-gradient and space-charge, 730–732
    thunder-storms and lightning, 738–740
Terrestrial-magnetic activity, 387
  characterization, 388
  diurnal variation, 398
  recurrence-tendency, 394
  seasonal variation, 397
  u-measure, 395
Terrestrial magnetism, bibliography, 693–724, 765–766
    classical and reference works, 695–698
    comparisons of instruments, 706
    cosmical relations, 717–722
    disturbances, 717–722
    expeditions, 699–701
    history, 693–695
    instruments, 701–706
    magnetic activity, 712–716
    magnetic anomalies, 722–724
    magnetic surveys, charts, etc., 708–711
    magnetism of rocks, 723–724
    methods of measurement, 701–705
    miscellaneous, 765–766
    observatories, 711–712
    periodic variations, 712–716
    permanent field, 706–712
    popular addresses, 701
    pulsations, 717–722
    secular variation, 716–717
    solar magnetism, 698–699
  comparison with atmospheric-electric phenomena, 385
  conventional subdivisions of phenomena, 400
  coordination with solar phenomena, 393
  early history, 1
  and earth-currents, 292
    general features, 291
    relations, 302, 432
  lunar variation, 545
    dynamo-theory, 546
    observational data, 545
  solar diurnal variation, 536
    corpuscular theory, 554
Terrestrial magnetism, solar diurnal variation, diamagnetic theory, 541
    drift-current theory, 542
    dynamo-theory, 537
    observed facts, 536
Thunder-clouds, shower-clouds, and their electrical effects, 657–678
  breakdown field in the presence of drops, 661
  charge on rain, 661
  charges developed and other electrical quantities involved in the thunder-cloud, 661–664
    dimensions of charged regions and potentials reached, 663
    energy, and current in lightning-discharge, 664
      spent in producing lightning, 664
    initial recovery-current, 662–663
    mean density of charge, 663–664
  distribution of charge on the thunder-cloud, 664–666
    lightning-branching criterion, 666
  distribution and frequency of thunder-storms, 674–675
  electric fields and field-changes at Earth's surface, 657–661
    discharge field-changes, 659–660
    fine-structure of field-changes, 660–661
    polarity of lightning-strokes to elevated conductors, 660
    sign and value of electric field, 659
  electromagnetic radiation-atmospherics, 672
  emission of electrified particles, effect on penetrating radiation, 672–674
  interaction of charged clouds with the ionosphere, 671–672
  interchange of electricity between electrified clouds and Earth, 670–671
    by ionic conduction, 671
    by lightning, 671
    by rain, 671
  lightning, 675–678
    component strokes of lightning-discharge, 675
    development of discharge, 677–678
    electrical effects of direct strokes, 675–676
    time-variation of current in the discharge, 676–677
  mechanical power available for generation of charge, 670
  origin of cloud-charges, 666–670
    charge on rain, 669–670
    of Elster and Geitel, 667–668
    of Gerdien, 667
    of Simpson, 668

Thunder-clouds, origin of cloud-charges, theories, 666–669
    thunder-cloud theories, 669
      discussion, 669
    of Wilson, 668–669
Thunder-storms, bibliography, 738–740
  distribution and frequency, 673, 674
Tromsö, Norway, earth-current measurements, 272
Troposphere, 492
Tucson, earth-current measurements, 272, 276, 285, 294, 295, 299
27-day recurrence of magnetic disturbance, 436
27-day recurrence-tendency of terrestrial-magnetic activity and solar phenomena, 388
  explanation, 390
  tests, 390

U

Ultraviolet light of the Sun, ionization by, 514
Ultraviolet-light theory, of aurora, 409, 557
  general assumptions, 555
  of magnetic storms, 409, 559
u-measure of magnetic activity, 395
United States Coast and Geodetic Survey, 67, 68, 73, 84, 91, 93, 685
  observatories of, 91
  publications of, 685
Upper atmosphere, 492–572
  composition of, 641
  defined, 492
  electrical state of, and the terrestrial corona, 647
  electrodynamics of, 531–535
    conductivity, 533–534
    crossed fields, motion of ions in, 534–535
    diamagnetism, 535
    dynamo-effect, 535
    ionization of upper atmosphere, 531–532
    long and short free-path regions, 532–533
  ionosphere, 501–514
    Breit-Tuve radio-echo method, 502–505
    E-region, 506–509
    F-region, 509–511
    during solar eclipse, 512–513
    during sunspot-cycle, 513–514
    three ionized regions of the high atmosphere, 501–502
  lunar terrestrial-magnetic variation, 545–547
    dynamo-theory, 546–547
    observational data, 545–546
  magnetic storms and aurorae, 547–564
Upper atmosphere, magnetic storms and aurorae, beam- and flare-theories of solar outbursts, 562–564
    corpuscular theory, of aurorae, 555
      of magnetic storms, 554–555
    data, of aurorae, 553–554
      of magnetic storms, 547–551
    disturbance-relations of radio, ionosphere, and Sun, 551–553
    ultraviolet-light theory, of aurorae, 557
      general, 555
      of magnetic storms, 559–562
  meteorology of, 492–501
    molecular density, 495–498
    propagation of sound-waves, 499–501
    temperature, 494–495
    wind-mixing and diffusion, 492–494
    winds, 498–499
  molecular density of, 495
  ozone in, 568–572
  skip-distances of radio waves, 528–531
  solar-diurnal variation of terrestrial magnetism in, 536–545
    diamagnetic theory, 541–542
    drift-current theory, 542–545
    dynamo-theory, 537–541
    introductory account, 536
    observed facts, 536–537
  temperature of, 494
  theory of, 514–528
    E-region, 524–525
    F_1-region, 525–526
    F_2-region, 526–528
    theoretical ionization-curves, 517–523
    ultraviolet light, 514–517
  zodiacal light and gegenschein, 564–568
    atmospheric theory, 567–568
    observational data, 564–566
    planet-dust theory, 566–567

V

Variations of the Earth's magnetic field, 5–13
  annual, 41–42
  causes, 53–54
Variometers, for declination, 80–81
  for horizontal intensity, 81–82, 86
  induction-variometer, 84–85
  for vertical intensity, 82
Virtual height, defined, 505
    (*See also* Ionosphere; Upper atmosphere)

W

Wait's ionization-apparatus, 264
  description, 264
  operation, 265
"Water-fall-" or Lenard-effect, 169

Watheroo Magnetic Observatory, 22
  diurnal variation at, 36, 38, 40
  earth-current measurements at, 272, 276, 279, 282, 291, 294, 299, 302
  location with respect to atmospheric-electric observations, 199
Wegener's hypothesis of drift of continents, 428
Wilson, C. T. R., apparatus for measuring variations in thunder-cloud fields, 658
Wind-mixing in the upper atmosphere, 492
Winds in the upper atmosphere, 498
Wulf electrometers, 234, 243, 249, 263, 265 (*See* Electrometers)

Z

Zodiacal light, 564–566, 654–656
  atmospheric theory of, 567–568
  planet-dust theory of, 566–567